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# THE IMPROVEMENT OF AN ELECTRONIC POWER SUPPLY FOR GREATER RELIABILITY IN AEROSPACE USE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1969

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## ABSTRACT

This report is a brief account of an upgrading program for electronic equipment. Serious design obstacles were overcome that led to the successful development of a highly reliable electronic component for space use. The component discussed is an inverter that provides three-phase 400-Hz power to the Centaur space vehicle. Because of early ground failures and design deficiencies, the inverter has received much engineering attention. This report is concerned with general upgrading of all piece parts used in the inverter, as well as improved mechanical and thermal design. Weaknesses of original piece parts are described, and rationale presented for the choice of better parts.

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## SUMMARY

This report is a brief account of an upgrading program for electronic equipment. Achievement of successful technical and managerial cooperation between government and industry is related, as executed at the working engineer level. A project is described in which a trustworthy component is developed by engineers who are not infallible, from parts that are not perfect. Serious design obstacles were overcome that led to the successful development of a highly reliable electronic component for space use.

The component discussed is an inverter, which changes electric power from direct to alternating current. This inverter provides three-phase 400-hertz power to the Centaur space vehicle. Failure of this inverter in flight would remove alternating-current power from the guidance system, resulting in loss of mission. Because of early ground failures and design deficiencies, the inverter received much engineering attention. This report is concerned with the second part of a two-phase improvement study. The first phase was undertaken to find solutions to specific circuit problems discovered in early ground testing of the inverter. The second phase, described in this report, was concerned with general upgrading of all piece parts used in the inverter, as well as improved mechanical and thermal design. Weaknesses of original piece parts are described, and rationale presented for the choice of better parts.

The improved inverter has been used successfully in 11 Centaur launches. Associated major systems ground tests total about 2000 operating hours without inverter failure in vehicle operation. Life testing, at ground environmental conditions, has accumulated about 12 000 hours, without failure.

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# INTRODUCTION

The development of reliable power conditioning[1] equipment for aerospace use has been a serious design problem for all engaged in this field. For example, both the Department of Defense and the National Aeronautics and Space Administration conclude that "It has been estimated that 90 percent of the space power systems failures or malfunctions have been in the power conditioning equipment" (ref. 1). This source goes on to say that such equipment is usually custom built rather than standardized, and that the usually short development times available provide little opportunity for developing reliability and "debugging" [sic]. Further, the problem is recognized in reference 1 as a system problem "lying principally with application groups," and that "research laboratories find it difficult to make a significant impact . . . for this reason. Progress is more likely to result from Research and Development (R&D) Groups working with flight hardware groups." In this instance, the R&D group is NASA's Centaur Project Office, and the hardware group is the Convair Division of General Dynamics Corporation.

Another authoritative source (ref. 2) states "The answer to the problem of electronic reliability, or the lack of it, lies in the maturity of engineering work, especially as it applies to the design and application of component parts." It is further stated that "The unreliability of much of the present equipment is due not so much to unreliable components but, in many cases, to their improper use in circuits and to improper mechanical designs." Engineering responsibility is again pinpointed in reference 3, in which the U.S. Navy Electronics Laboratory says that "Lack of good engineering in the development and prototype design stages is the major underlying reason for equipment failure. It would seem that engineers, in striving primarily for performance, tend to lose sight of reliability. Another engineering failing is the incorrect use and misapplication of the normally reliable and approved component (part). A system or an equipment can be 'sick' as well as a man, and it is very difficult to measure exactly how sick it is." (ref. 4).

This report is a case history of a product improvement program. It does not resort to "elaborate mathematical exercises" to predict reliability, nor to construct a reliability model. Advanced mathematical concepts certainly have their place in the field of reliability, but this report is written from the viewpoint of the design engineer, trained in the experimental method. "The use of the statistical method in formulating reliability concepts often represents a barrier for the engineer." (ref. 4). The traditional education of the engineer is founded on the experimental method and the reproducible experiment. This philosophy is quite different from the statistical method. In the present

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[1]Power conditioning (electrical) is defined as the process of changing voltage, current, or frequency level of electrical energy.

case, engineering experience and design practice principles are applied to the improvement of an existing design.

Although the actual flight record of the earlier equipment was free from failure, the improvement program resulted from numerous failures experienced during ground checkout of the inverter and/or associated systems. Three major problems were attacked:

(1) Thermal limitations of the inverter

(2) Structural vibration deficiencies

(3) Inadequate piece part quality

The methods employed in solving these problems were

(1) Improving thermal conductivity from hotspots to radiating surfaces

(2) Stiffening critical sections and incorporating modularized subassemblies

(3) Selecting parts to established upgraded standards of quality and reliability, and imposing proper tests to verify quality

(4) Using design reliability checklists (refs. 5 and 6)

The fact that this inverter uses discrete components, rather than microelectronic circuitry, does not make the inverter obsolete. There are many classes of aerospace electronic equipment which are now and will continue to be so designed and constructed, especially at power levels of the magnitude involved here. Since this equipment is representative of a large class of similar equipment, a discussion of quality upgrading is included to assist the designer.

## DEVELOPMENT HISTORY

Development of the Centaur inverter has been characterized by a unique combination of government and industry engineering efforts. For example, early work on the identification of critical electrical aspects of the design was done at the Lewis Research Center (ref. 7). During this study, engineers learned that industry had made available piece parts of quality levels superior to those then used in the inverter. Also, it was discovered that some parts were misapplied. Such errors are considered by some writers (ref. 8) to be the major cause of parts failures. Joint design reviews were held to identify these deficiencies and to plan a long-range improvement program.

In the meantime, flight data (refs. 9 to 18) and contractor vacuum chamber tests revealed that the thermal design of the inverter was not adequate for long coast missions (an hour or more in the space environment). Since such missions were planned to become an important part of future Centaur capability, it became imperative to improve the inverter in this regard.

It was decided to make major modifications in the inverter design, to qualify the new design, and to fly it before the launch vehicle became operational. Since the time availble was only about a half year, the work was undertaken on a priority basis by a combined "tiger team" of government and industry engineers. The tiger team proceeded with an operating plan containing the following elements:

(1) Definition of requirements

(2) Isolation of problem areas

(3) Analysis and development of problem solutions

(4) Application of results to the design

(5) Proof of analytical results

(6) Maintenance of control during all development activities

An important step in executing this plan was the use of design reliability checklists such as those given in reference 6. No single designer, or even groups of designers, can be expected to retain the experience necessary to consider properly each significant characteristic of design for failure prevention. It is therefore essential to accumulate this experience in comprehensive checklists. These checklists, along with the appropriate analysis methods, provide the design engineer with the best possible tools to design for inherent reliability. In turn, these checklists can be used as a part of the design process to help the reviewers in considering the most pertinent causes of unreliability.

In the interest of improving design margins of all Centaur vehicle components, it had been a program objective to impose on all "new build" equipment vibration qualification levels increased by 50 percent over those originally specified. Briefly, the new levels called for 0.225 $g^2$ per hertz from 600 to 1100 hertz (random) and 4.5 g's rms from 600 to 2000 hertz (sine wave), combined. From 13 to 600 hertz, the sine wave level is 3.15 g's rms, and 0.25-inch (0.64-cm) half amplitude below 13 hertz (see fig. 28 for details).

When the first generation inverter was subjected to these higher levels, the quartz crystal oscillator failed, and stroboscopic studies showed large amplitude vibrations of various parts of the inverter. This led to the conclusion that mechanical redesign was necessary as well as the electrical and thermal redesign already mentioned. Mechanical redesign also provided the opportunity to simplify subassemblies and harnessing so as to improve the quality of manufacturing and test operations.

The developments described in this report began with government engineering initiative to introduce high-reliability[2] parts, as well as to provide increased thermal and vibration capability margins. Ground rules and criteria for parts selection were provided, and joint efforts directed toward optimum selections. Greater confidence was desired in assembly and test procedures, especially at the subassembly level. Intensive analysis

[2]High reliability is a relatively new term which has come to represent a failure rate of 0.001 percent per 1000 hours (or better) at 90 percent confidence (ref. 19). Reference 19 presents an interesting discussion of parts improvement and selection for aerospace use.

was made of observed failures. This resulted in quick response and corrective measures leading to the "second generation" design. The new design was completed, manufactured, qualified, and flown within a 7-month period.

All flights of the Centaur, which is now operational, employ the new inverter. Performance of the inverter is described in flight reports (refs. 9 to 18). Details of problems encountered and their solutions are presented in the following sections of this report.

## DISCUSSION AND RESULTS

This part of the report is organized into two sections, according to the engineering disciplines: mechanical and electrical. Major problems in each area are described in the first part of each section, and then solutions to these problems are grouped together in the second part. For convenience, each part is further divided into subsections of related subject matter. Thermal aspects are included in the section MECHANICAL ASPECTS.

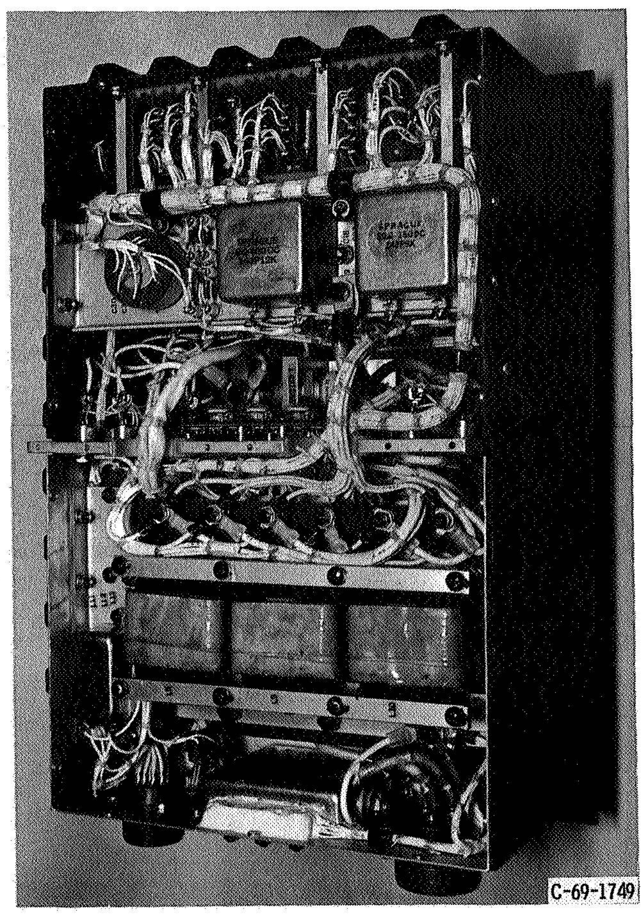



Figure 1. - Top view of original inverter.

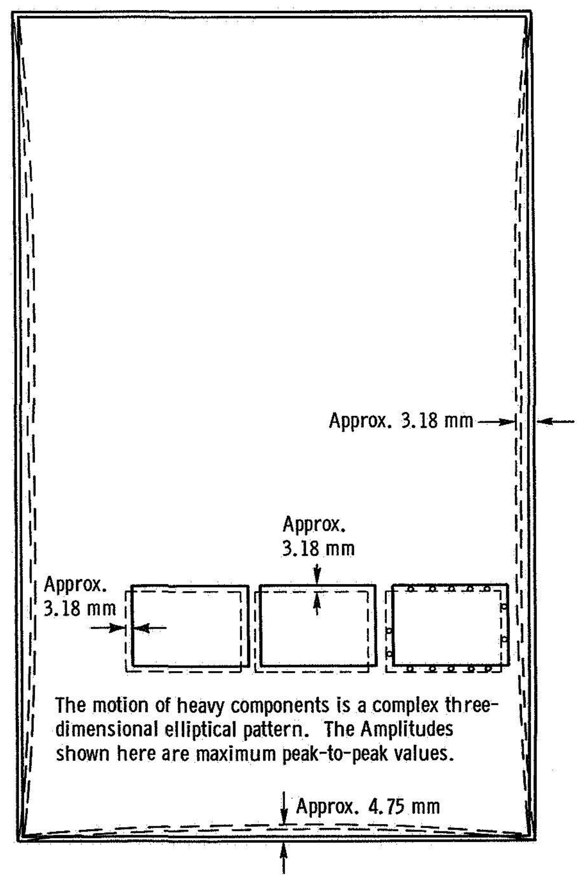



Figure 2. - Major vibration modes of original inverter.

# MECHANICAL ASPECTS - PROBLEMS

## Vibration Susceptibility

The original Centaur inverter (fig. 1) was subjected to a three-axis vibration-mode study to determine various component Q (resonant amplification) factors and frequencies. The tests were conducted with a 2-g (peak-to-peak) sine sweep rate of 2 minutes per octave. Six accelerometers were mounted throughout the unit, and a stroboscope and cine-camera were employed. Analysis of films showed that the inductors (weighing 2.3 kg or 5.1 lb) moved in a three-dimensional elliptical pattern (fig. 2). The front face and side of the case oscillated with a peak amplitude of approximately 3.2 millimeters (0.125 in.). Accelerometer data indicated a Q of 12 at a frequency of 125 hertz in the areas mentioned. The transformer (weighing 5.1 kg or 11.2 lb) mounting area had a Q of 12 at approximately 130 hertz. In addition, the accelerometer at the capacitor group (weighing 1.6 kg or 3.5 lb) showed a Q of 14 at 220 hertz.

## Parts Layout and Assembly

A thorough review of the existing inverter packaging revealed areas of marginal design and a number of quality control problems. The existing design of components (i.e., three-phase transformers and inductors) and assembly of components (i.e., connectors, capacitors, and terminal boards), made the unit extremely difficult to fabricate. Fabrication complexity too frequently leads to human error, quality control problems, and potential failures. The primary fault in the design was that the wiring was adjacent to sharp edges of bracketry and exposed screw threads, with the resultant possibility of electrical short circuits during flight vibrations. Parts of the harness were required to assume tortuous paths (poor routing), were difficult to prefabricate, and were even more difficult to terminate at the proper points. In some cases, terminations consisted of splices - always a questionable procedure. In other cases, there were too many wires connected to a single terminal.

In addition to the design problems mentioned, there were quality control defects which had to be overcome if the inverter was to be improved. Among these deficiencies were poor lead dress, harness tying, stripping, terminating, and inadequate clearances. Specific faults were nicked wires, charred insulation, presence of solder balls, lack of stress relief at terminals, improper cleaning (lack of rosin removal), and the use of incorrect size crimping tools. In short, almost every possible kind of electronic manufacturing malpractice was evident to some degree in the first generation product. The improvement program, then, required not only engineering redesign, but personnel training and workmanship quality enforcement as well.

## Thermal Design

The current-sensing resistor subassembly R53 (see diagram in appendix) was originally mounted to the main heat sink yet insulated from it with a thin mica spacer. Up to 10 watts heat dissipation capability was required, depending on load. The design of the existing inverter utilized a number of parts for this subassembly. It was essential that these parts be assembled with extreme care (again subject to human error) in order to ensure proper electrical insulation, yet to obtain good thermal conductance. For example, the inadvertent use of more than one piece of mica seriously degraded thermal conductivity to the case, so that the resistor overheated. Also, the resistor element was subject to metallic burrs, again due to human error or oversight, and could eventually short to ground because of movement due to thermal expansion and contraction. Such an incident did occur (ref. 20 and fig. 3).

The original packaging design of the Centaur inverter did not provide sufficient thermal sink to prevent certain electronic components from exceeding their temperature rating (e.g., 398 K at the silicon-controlled rectifier (SCR) junctions). Flight data (fig. 4) clearly show that temperature margins approached zero after about 1/2 hour of flight time for the old inverter. Changing to higher temperature rated components (423 K) did

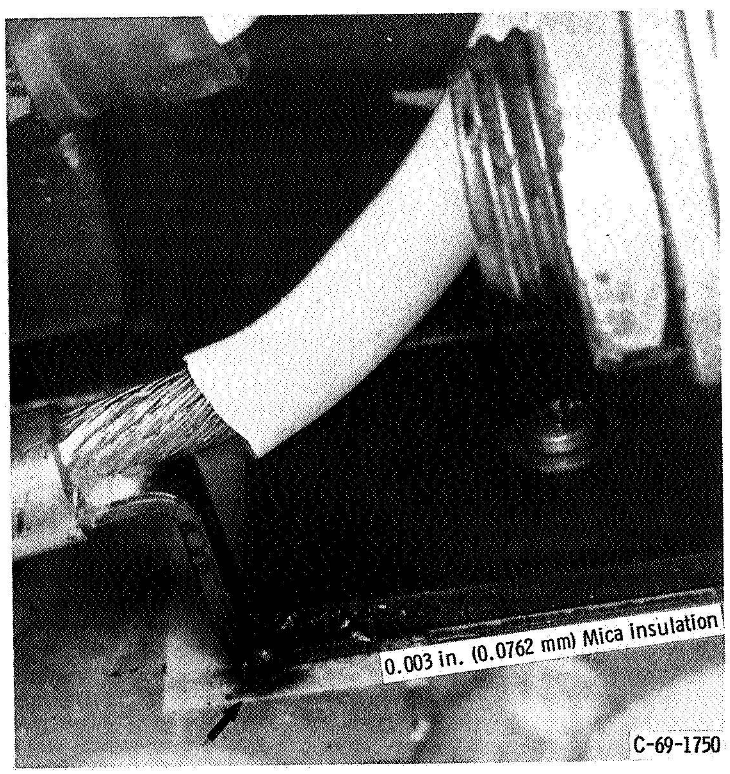



Figure 3. - Insulation failure mode of resistor R53.

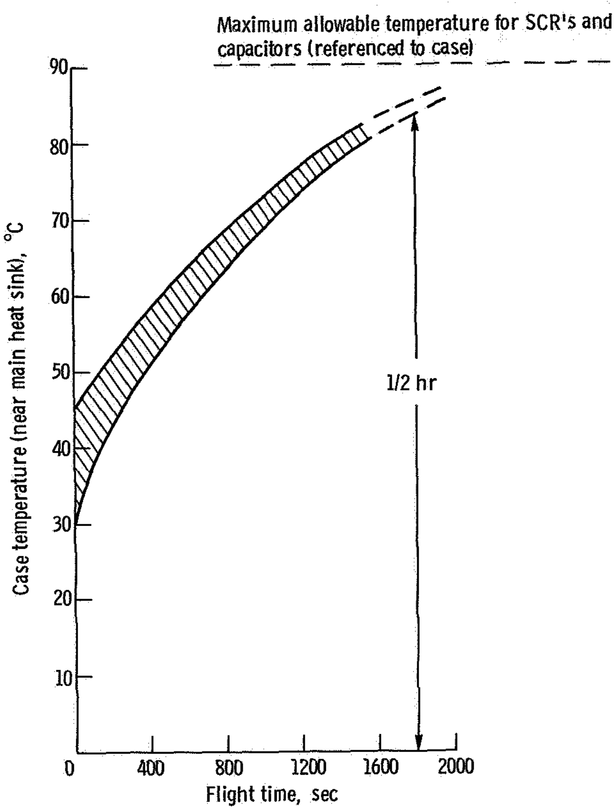



Figure 4. - Range of observed flight temperatures of original inverter design.

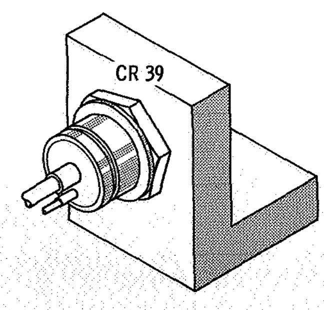



Figure 5. - Main drive SCR (CR 39) in original mounting.

increase the thermal margin; however, it did not improve the thermal conductance.

The main drive SCR, CR39 (see appendix), was originally mounted to an L-bracket (fig. 5) that provided a marginal thermal path. This path began at the SCR face, and the conductance was sensitive to the perpendicularity between the SCR face and thread axis. The thermal resistance of this design resulted in a temperature gradient as high as 65 $C^{o}$, which caused CR39 to operate near its thermal limit, in the overload mode of operation.

## Other Related Problems

There were several other mechanical (and chemical) areas of concern. One was the use of conformal coatings on circuit boards. Conformal coatings are used to improve the vibration resistance of circuit boards by sealing small parts to the board to prevent relative motion. The coating must have good adhesion and thermal properties, yet must not crack glass diodes as the coating hardens.

A more subtle problem was related to contamination of nickel plated, Teflon-insulated wire. It was learned from D. Grau, Director of the Quality Assurance Division at the Marshall Space Flight Center, that "one of the drawbacks of Teflon has been its failure due to corona stress." The resultant release of fluorine gas results in the formation of

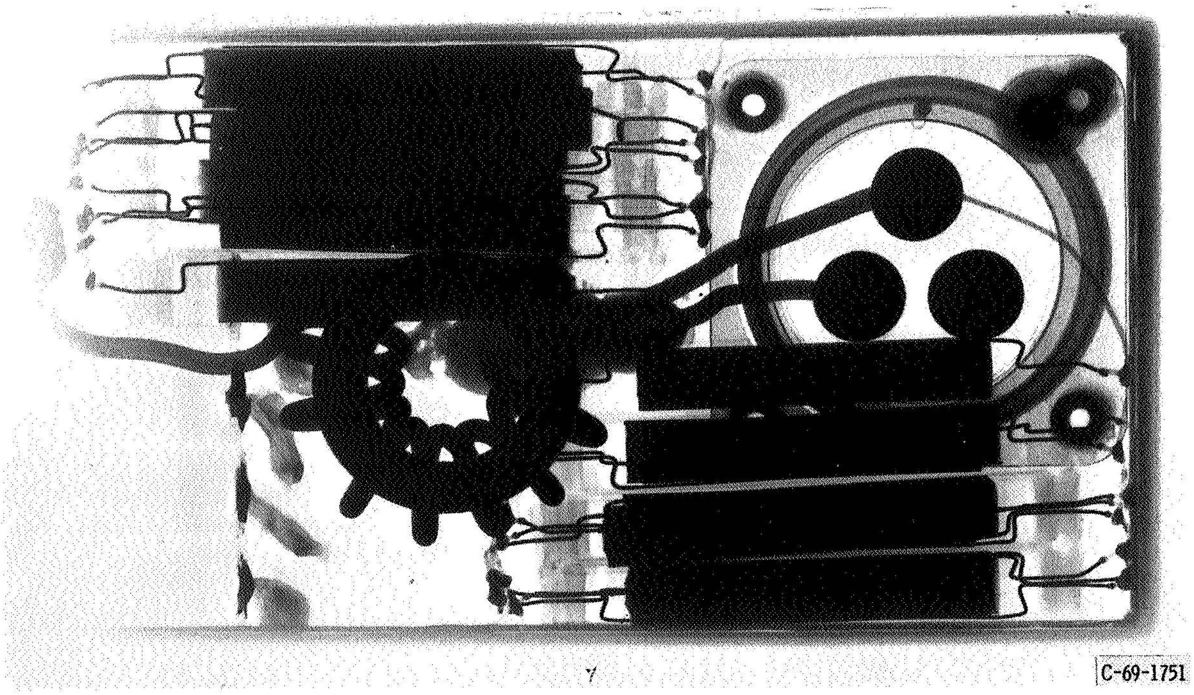



Figure 6. - X-ray view of noise filter.

hydrogen fluoride which reacts with the copper wire or nickel coating to form a surface contaminant. The contaminant may reduce the conductivity at connector interfaces.

Even more insidious is the quality of workmanship on purchased assemblies such as noise-suppression filters. These are commonly potted, and the only way to check on internal workmanship is by X-ray (fig. 6). Here, the quality level evident is typical of such devices and is unsuitable for aerospace use because of possible short circuits due to poor parts layout, wire routing, and fastening methods. This component is usually a proprietary vendor item. Improvement in this area calls for controlled procurement.

## MECHANICAL ASPECTS - SOLUTIONS

### Improved Rigidity

The primary structural redesign measures in the forward compartment of the inverter included the addition of rib stiffening to the inverter base, provision for continuous support of the three-phase transformer, and the addition of stiffeners to the housing sides and faceplate (fig. 7). The aft compartment was significantly stiffened through attachment of the capacitor module, which is discussed in the next section. The vibra-

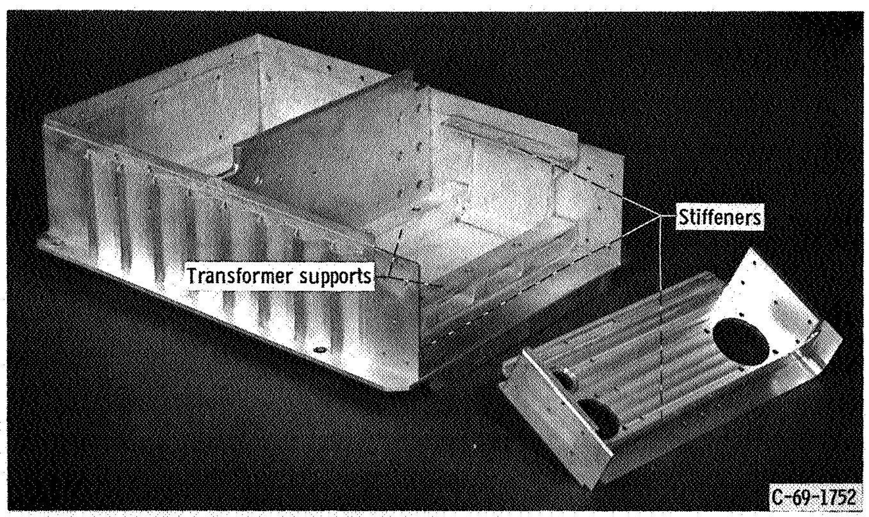



Figure 7. - Primary structural redesign features.

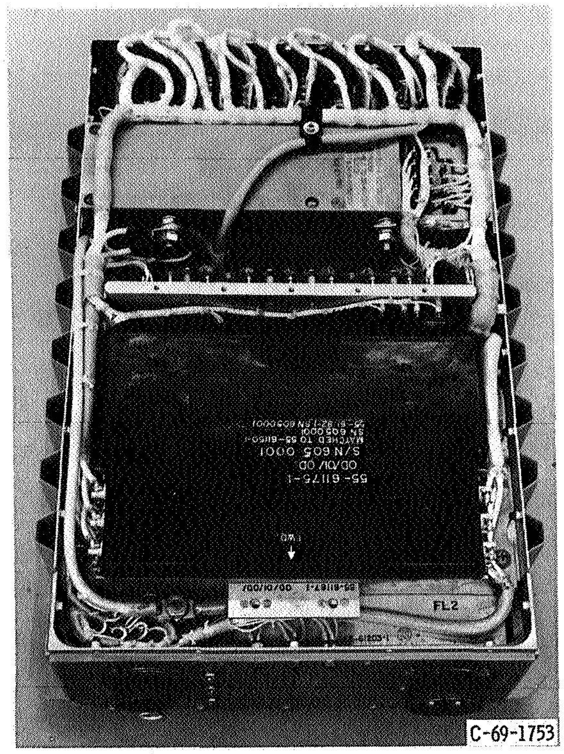


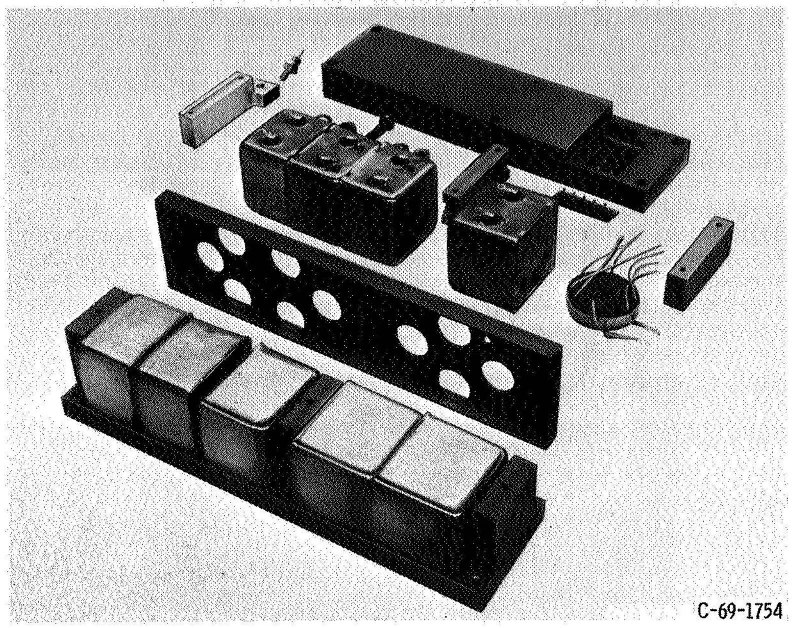

Figure 8. - Top view of new inverter.

tion mode study of the redesigned and repackaged unit (fig. 8), conducted under the same conditions as before, showed the Q factor for the critical areas to be reduced to approximately 5.

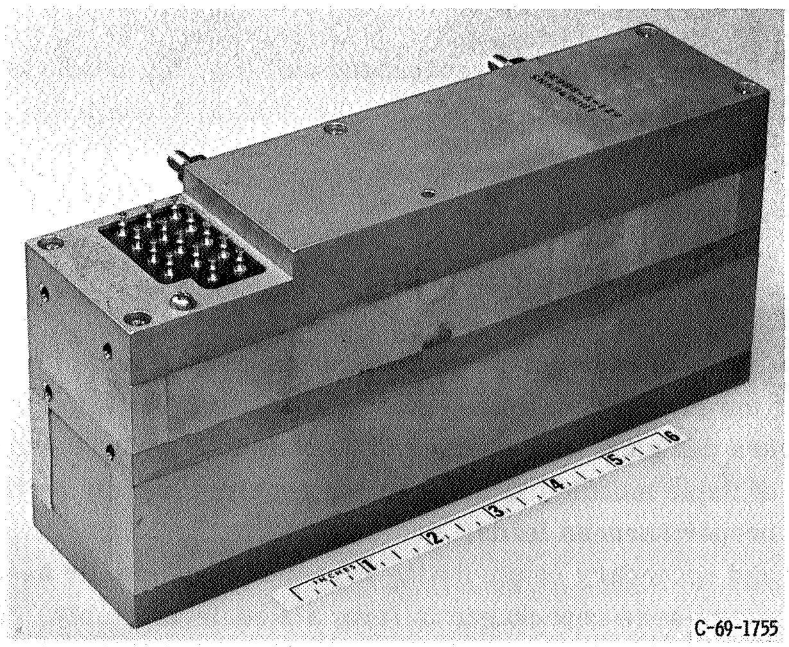
## Parts Repackaging and Assembly

During the mechanical redesign period, the decision was made to use a module concept for packaging the inverter. Various components, such as transformers, inductors, and capacitors, were designed into modules to be complete within themselves. Subsequent installation of these modules in the inverter required merely bolting them in place and soldering the proper harness leads.

The primary and secondary commutating capacitors, originally assembled in chassis-type mounting, were repackaged to form a module assembly. The original design was difficult to install and wire, and impractical to pretest functionally before assembly into the inverter. The modular redesign utilizes feed-through terminals in an accessible position for harnessing after final assembly. The feed-through terminals permit the harness to be attached to the module so that a complete inspection of the

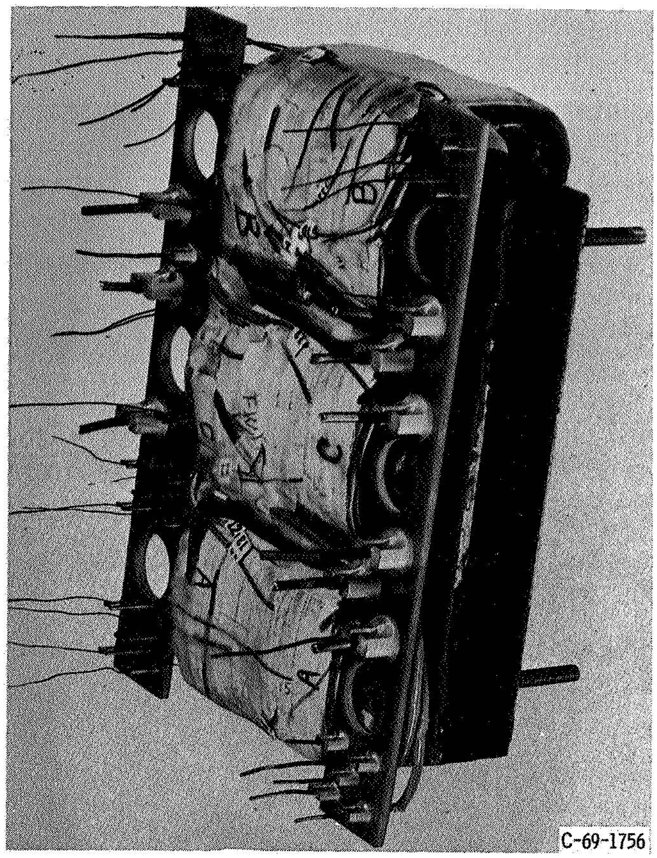



(a) Arrangement of components.

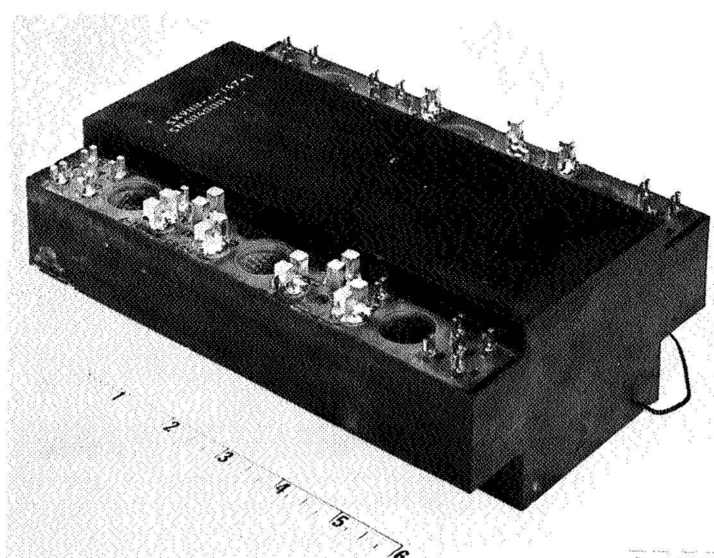



(b) After potting.

Figure 9. - Capacitor bank.




(a) Before potting.

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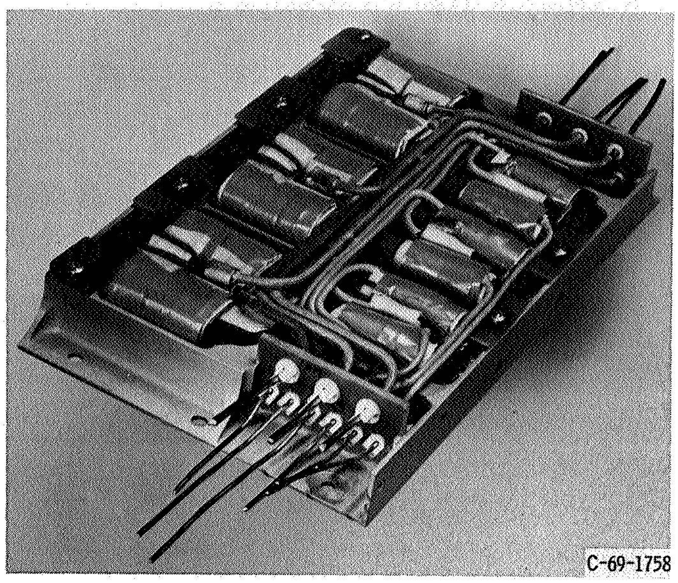
(b) After potting.

Figure 10. - Power transformer.




(a) Before potting.


(b) After potting.

Figure 11. - Inductor assembly.

solder points can be made after the final operation. This design also provides improved vibration resistance and thermal sink for these critical capacitors (fig. 9).

The three-phase power transformer and the six inductors were originally built with spliced leads that had to be routed to specific termination points throughout the inverter during final assembly. The modular concept provides subassemblies without splices directly to the wire itself. The internal leads from the transformer and inductor modules are terminated in feed-through solder terminals. This type of design provides a subassembly which is readily tested (fig. 10). The redesigned inductor module is shown in figure 11.

Figures 12 and 13 illustrate steps in the redesign process. The design shown in figure 12 employs improved parts but is essentially the original mechanical configuration. Figure 13 shows the improved configuration.

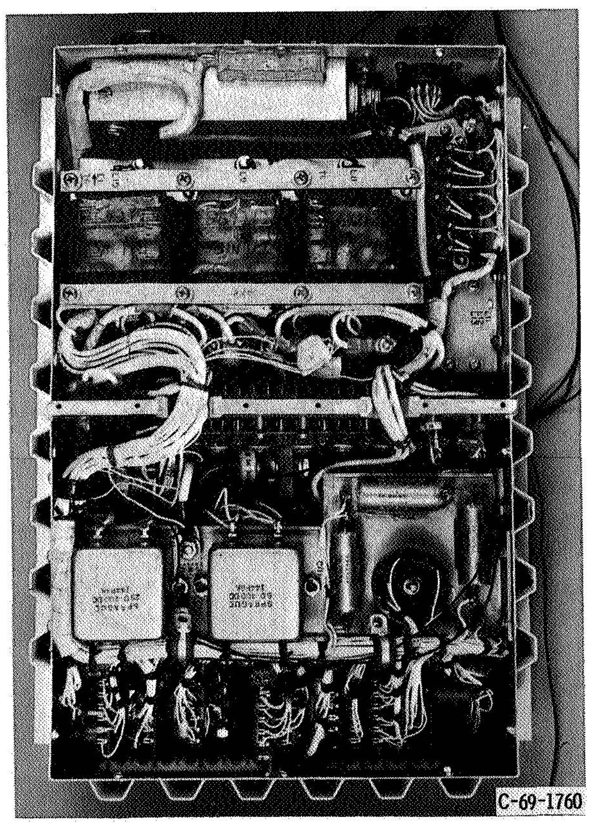



Figure 12. - First redesign configuration of new inverter.

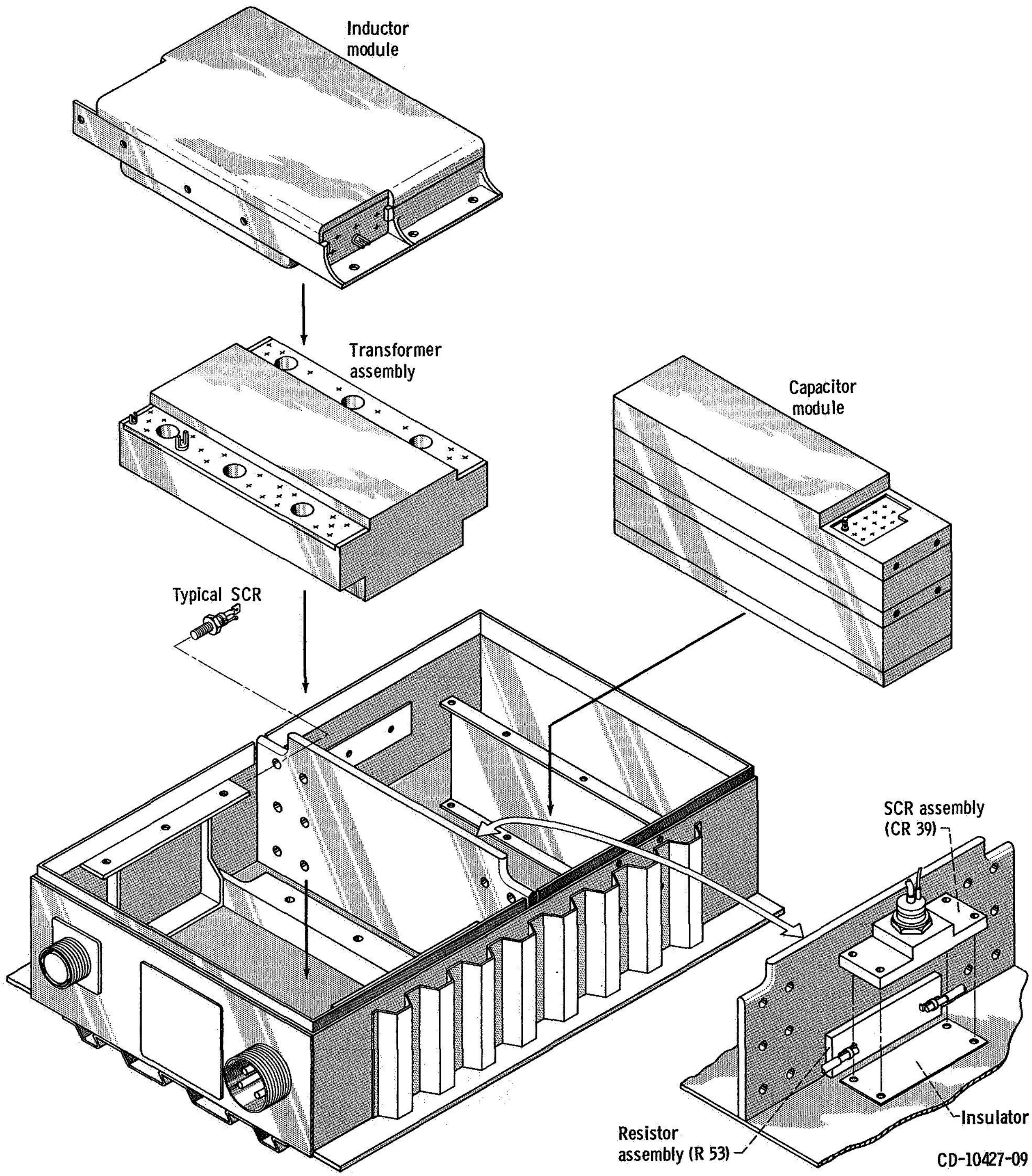



Figure 13. - Final redesign of new inverter showing modular construction. (Circuit boards are not shown.)

## Improved Thermal Design

Inverter redesign for improved thermal performance employed the checklist on page 6-13 of reference 5, as well as the design aids cited in reference 6. The main-drive SCR (CR39) installation was redesigned to employ a T-shaped bracket with the SCR mounted directly by its threads (fig. 14). The effectiveness of this design can be evaluated by the temperature difference between the SCR case and the external inverter case directly opposite the mounting. For the new design, the difference is 45 $C^{O}$; for the old it was 65 $C^{O}$. The improved thermal conductivity extends the useful operating life in space environments.

The current-sensing resistor, R53, assembly was redesigned to use a minimum number of parts and to eliminate complex assembly in an inaccessible or "blind" spot in the inverter (also shown in fig. 14).

The mechanical redesign of the inverter improved the thermal profile, as shown in figure 15, which is a composite of actual temperature data from six flights. The width of the bands represents temperature differences at lift-off, as well as differences caused by variation in mission profiles, for instance, length of coast and exposure to solar radiation. The actual improvement is even more marked than indicated by figure 15 because the temperatures of the old inverter were sensed on the skin of the inverter, while the temperatures of the new inverter were measured on an internal heat sink, much nearer

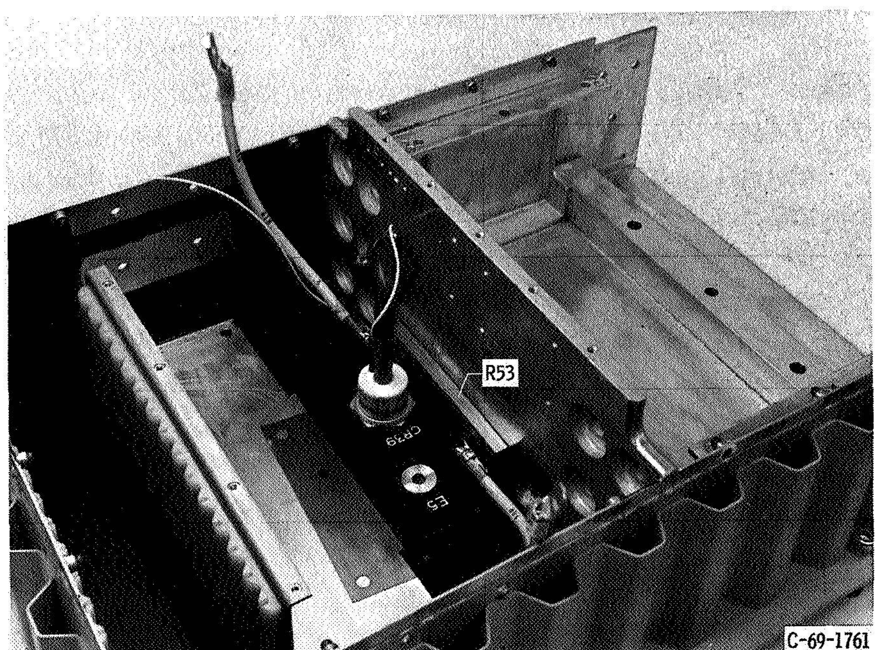



Figure 14. - Control rectifier CR39 and resistor R53 heat-dissipating mountings.

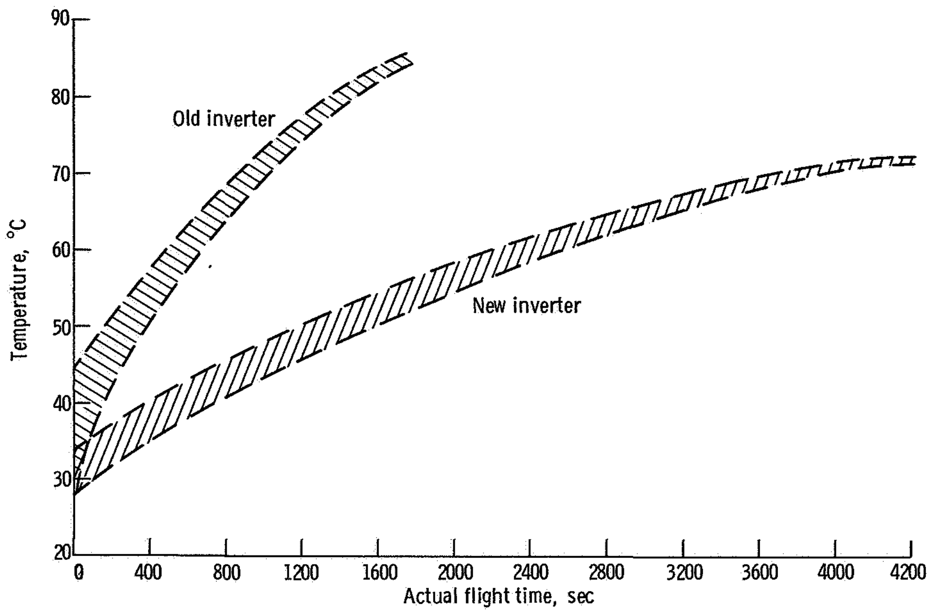


Figure 15. - Range of flight temperatures observed for old and new inverters.

to the SCR hotspots. A difference of about 12 $C^{o}$ is attributable to this change in temperature sensor location alone.

Temperature influence on the failure rate of electronic parts is well known. The reliability improvement of the new inverter, because of its cooler operation, is the outstanding feature of the design change.

The commutating capacitors, previously described, were severely temperature limited. Originally these 25-microfarad capacitors were of metallized paper construction in which the electrodes consisted of very thin films of metal (25 to 100 m$\mu$m thick). Because of this thickness, internal heat conductivity was poor, and the capacitors were limited to about 343 K for 100 percent ac stress. The original inverter design provided little conductive dissipation for the heat generated within the capacitors (see section on electrical parts). The new module, filled with a thermally conductive potting compound (conductivity: 0.23 Btu/(hr)(ft)($^{o}$F) for 14 J/(hr)(cm)($^{o}$C)) provided the required conductive medium and consequently improved the capacitor temperatures in the environment of space.

## ELECTRICAL ASPECTS - PROBLEMS

### Capacitors

The most serious design deficiencies in the entire inverter were found in this area of parts application. Originally, there were several cases both of misapplication of parts and of narrow design margins. The misapplications related to the use of metallized capacitors in the shift register (C9 to C14) and the use of tantalum capacitors. In the case of commutating capacitors, with high-energy storage and high rates of energy change, thermal design margins were not well understood. Consequently, there was low confidence in reliable operation at high temperature.

Atlas and Centaur capacitor failure experience is summarized in tables I and II. Capacitors C1, C33, and C35 (see circuit diagram (fig. 27) in appendix) were types not qualified for space use because of seal leaks. They were rated for pressures equivalent to an altitude of only 80 000 feet (24 km) and then only for 5 minutes of operation. For example, internal leakage current increased 30 times during vibration testing at 3000 hertz and 54 g's - a definite sign of atmospheric leakage at the seal (ref. 14).

Capacitors C18, C23, and C28 in the commutating circuit were operated at approximately 76 volts rms, 400 hertz, and were stressed greater than 100 percent. Although their dc rating is 200 volts, the vendor engineering bulletin for metallized difilm capacitors gives the maximum ac rating as approximately 50 volts rms at 358 K.

Capacitors C39, C40, and C41 in the power transformer secondary circuit operated at 115 volts rms, 400 hertz, and were stressed over 100 percent. Again, the maximum dc rating is 400 volts, but the maximum ac rating is 80 volts rms at 358 K.

TABLE I. - DISTRIBUTION OF FAILURE[a]

MECHANISM BY CAPACITOR TYPES

| Capacitor type | Numbers of failure mechanisms | | | | |
|---|---|---|---|---|---|
| | Dielectric imperfection | Contamination | Fluid leakage | Cracked | Open bonds |
| Solid tantalum | 5 | 4 | -- | -- | [b]10 |
| Wet slug | 5 | 1 | 2 | -- | 1 |
| Tantalum foil | 2 | -- | [c]9 | -- | 2 |
| Paper | 2 | -- | -- | -- | [d]10 |
| Metallized dielectric and plastic | 1 | -- | -- | -- | [e]9 |
| Ceramic | 2 | -- | -- | -- | 1 |
| Glass | -- | -- | -- | 2 | -- |
| Mica | -- | -- | -- | -- | -- |

[a]Primary capacitor failures determined from failure analysis reports (FAR); airborne only.

[b]Four of 10 failures on vendor A capacitors for leads not firmly bonded to case.

[c]Corrosion on end found during receiving inspection.

[d]Six of 10 failures on vendor B capacitors for defective bonds.

[e]Seven of nine failures on vendor C metallized Mylar for broken bonds.

TABLE II. - RATIO OF CAPACITOR FAILURE[a] TO USE POPULATION[b] FOR VARIOUS CAPACITORS

| Capacitor | Failure in population | Number of capacitors in population | Ratio failure to population |
|---|---|---|---|
| Solid tantalum | [c]17 | 221 | 0.077 |
| Wet slug | 8 | 50 | .160 |
| Tantalum foil | 3 | 67 | .045 |
| Paper | [d]11 | 99 | .111 |
| Metallized paper and plastic | [e]8 | 39 | .205 |
| Ceramic | 2 | 85 | .023 |
| Glass | 2 | 40 | .050 |
| Mica | 0 | 5 | 0 |

[a]Primary capacitor failures determined from failure analysis reports (FAR); airborne only.

[b]Numbers and types of capacitors estimated in airborne Atlas and Centaur autopilot, electrical and propellant utilization systems and Atlas telemetry package.

[c]Four of 17 failures on (vendor A) capacitors for leads not firmly bonded to case.

[d]Six of 11 failures on (vendor B) capacitors for defective bonds.

[e]Seven of eight failures on (vendor C) metallized Mylar for broken bonds.

## Semiconductors

The second most highly stressed kinds of parts used in this inverter were the semiconductors, especially silicon controlled rectifiers (SCR's). Maximum junction temperature is the limiting criterion in space operation of SCR's. An SCR limited to 373 K at the case reached this limiting temperature after about 1/2 hour of solar exposure environment.

The pulse firing characteristics of an SCR are unspecified parameters for the durations and levels used in the inverter. Further, different applications within the inverter of the same type of SCR imposed different requirements. The commercially available SCR was not manufactured to a military specification, nor was it X-rayed for defects or preconditioned electrically or thermally. The consequences of failure to X-ray are shown in figure 16, in which the lack of adhesion of wafer and substrate is clearly evident. Although the SCR initially tested "good," after prolonged operation a hotspot developed which ultimately led to burn-through and short circuit.

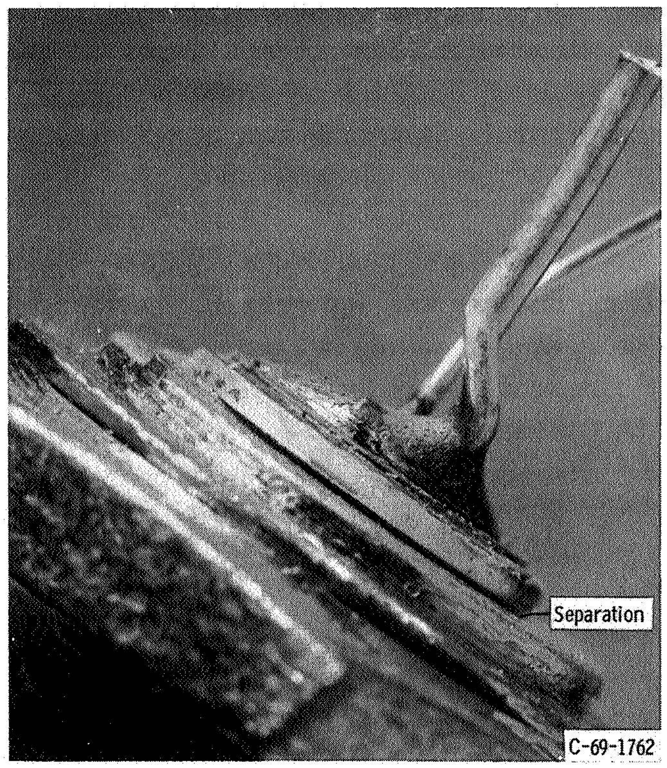



Figure 16. - SCR failure (wafer separation).

Diodes and transistors were, in general, commercial-grade semiconductors and were not manufactured or tested to military or high-reliability specifications. They were formerly of the "MESA" design, in which the semiconductor wafer is etched down in steps so that the base and emitter regions appear as plateaus above the collector region, and the chip surface is not passivated. Passivation is a process of protecting the surface of semiconductors from atmospheric degradation. Without passivation, the semiconductor is subject to contamination, moisture absorption, and leakage failures.

## Resistors

Resistors used in the inverter are of four general kinds: (1) composition fixed, (2) wirewound fixed, (3) film fixed, and (4) wirewound variable.

Problems with the composition-fixed resistor consisted principally of temperature stability and broken and pulled leads. Temperature stability problems were aggravated by less-than-conservative stress ratios and by failure to precondition the parts. Although the resistors were purchased to specification MIL-R-11A, quality variations existed among vendors.

The second type, wirewound resistors, displayed intermittent contact as well as broken leads. Originally, these were all commercial parts and were subjected to highly variable quality levels. The third, or film type of resistor, was formerly also a part not subject to specification control. The fourth type of resistor, or wirewound variable, was relatively free of problems (primarily because they are exercised only during calibration).

Resistors R61 and R63 in the Royer type power supply were operated at greater than 100 percent stress while the inverter was in overload. The voltage across R61 was approximately 10 to 12 volts rms, resulting in a power dissipation of more than 1 watt. (R61 was rated at 0.5 W.) Approximately 7 volts rms were developed across R63, and it dissipated about 0. 5 watt. (R63 is also rated at 0. 5 W.) A failure of either resistor would result in loss of overload protection.

## Magnetics

Under normal inverter operation, the excitation windings of the six memory cores in a shift register are pulsed simultaneously from the core driver circuit (CR12) at a 2400-hertz rate. The state of one core is normally at negative remanence (OFF). (Magnetic remanence is the magnetic induction remaining in a magnetic circuit after removal of the magnetizing force.) When an excitation pulse is applied to this core, it changes state to the positive saturation condition. The associated flux excursion will result in an output pulse (called the major, or desired pulse) across the resistor at the SCR gate winding, of at least 4. 5 volts. (Fig. 17 shows shift register selection criteria.) The other five cores, which are at the positive remanence state (ON) when pulsed, will experience flux excursion from the state of positive remanence to positive saturation. The associated output at the gate winding in this case is directly dependent on the "squareness" of the core's magnetic characteristic, which is depicted by the curve for flux density B as a function of magnetizing force H, or hysteresis loop. Squareness is defined as the ratio of a residual to peak flux density (ratio of flux density at positive remanence to that at positive saturation) and is typically about 0.96 for a high-quality core. This results in a very small flux excursion (from 0.96 peak flux density to peak) and an associated small minor (or undesired) output pulse (normally less than 0.2 V).

As the squareness ratio decreases, the flux excursion from residual to peak increases, and the minor or undesired pulses increase accordingly. In this event, one of the commutating SCR's may be fired out of sequence, resulting in momentary short circuit, overload, and "dropout" of the inverter. This kind of problem did, in fact, occur during the early fabrication and testing stages of the new inverter, thus making it essential to discover the reason for the deterioration of the B/H curves.

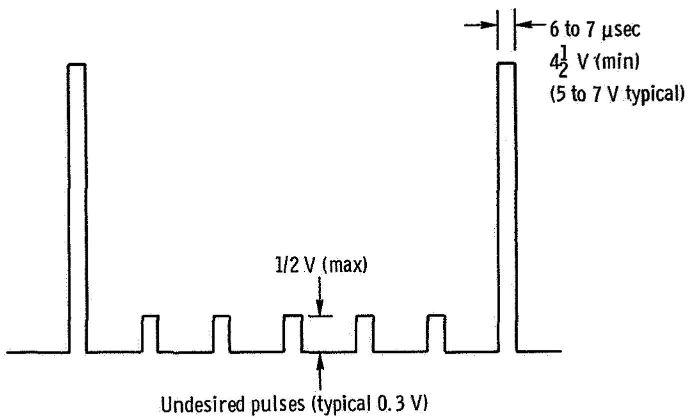



Figure 17. - Shift register selection criteria. Output from gate winding when loaded with 1000 ohms. Short circuit peak current, 400 milliamperes minimum.

# ELECTRICAL ASPECTS - SOLUTIONS

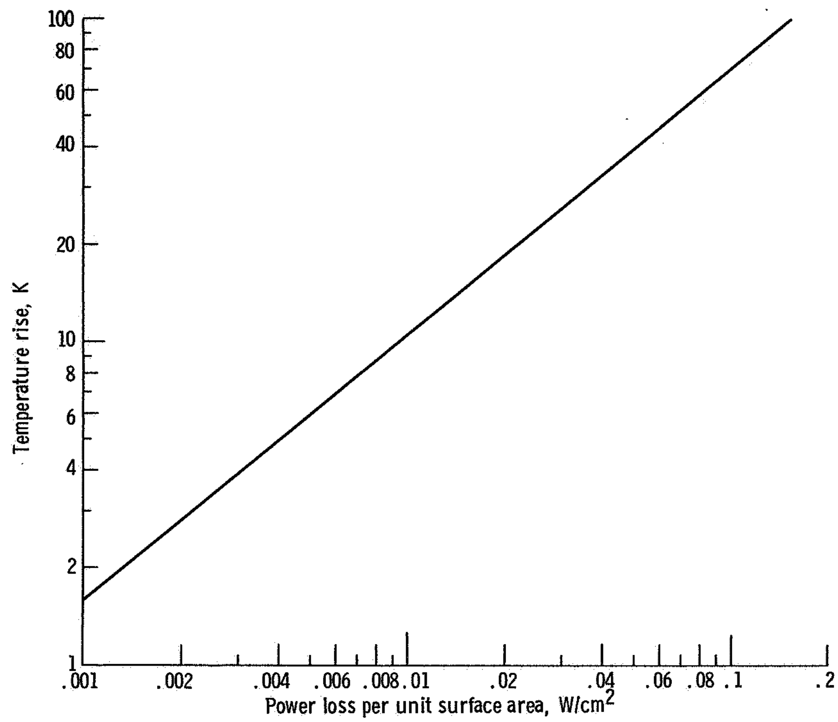
## Capacitors

The most heavily stressed parts in the inverter are the commutating capacitors C18, C23, and C28 (as well as C30, C30A, C30B, C39, C40, and C41). These capacitors are subjected to very severe energy storage requirements because a significant part of the output of the inverter flows through and is momentarily stored by them. Capacitor temperature rise is proportional to the energy stored (fig. 18(a) and ref. 2); further, the time derivative of current di/dt across the capacitor is high (ref. 7). While the physics of the failure mechanism due to steep wave fronts is not clear, evidence is available that such surges do cause deterioration (ref. 21).

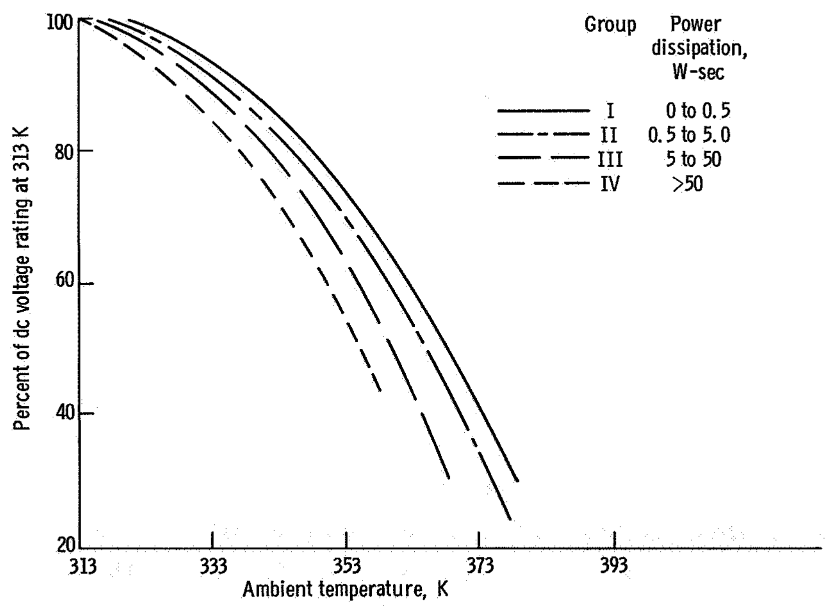
Although capacitors for this application are not available from military specification lists, the state of the art has improved sufficiently (ref. 22) so that operation at 398 K becomes possible at full rated voltage (dc). In addition, new capacitors will withstand a life test of 140 percent of rated voltage (ac) for 250 hours at full rated temperature, as well as overvoltage tests at twice-rated voltage (dc). The dielectric used consists of a dual combination of metallized paper and of polyester film, impregnated with a special high temperature mineral wax. Both government and contractor engineers worked with the vendor in the application of this part to the inverter. In addition to the usual tests performed by the vendor, all parts were subjected to the following ground rules:

(1) 50-Hour preconditioning at 140 percent of rated (dc) voltage

(2) 4-Hour preconditioning at 400 hertz and 358 K (Units rated at 200 V dc are subjected to 40 V rms ac, and units rated at 400 V dc are subjected to 75 V rms ac.)




(a) Temperature rise as function of watts per square centimeter power dissipation.




(b) Typical derating curves.

Figure 18. - Paper capacitor design data.

Derating practice for alternating-current service is described by the following criteria:

(1) The dc voltage (28 V) plus the peak ac voltage (76 V) shall be less than the dc rating of the capacitor.

(2) Under worst case operating conditions (maximum ac voltage and maximum ambient temperature), the sum ambient temperature and twice the case temperature rise shall be less than 400 K.

It is worth noting that these derating factors are far less restrictive than those imposed by the former state of the art (ref. 2, p. 142), shown herein as figure 18(b). It is apparent that these new capacitors represent a significant advance in the state of the art and make it possible to house the inverter in its present case size.

The two derating criteria listed were not exceeded during a simulated (vacuum chamber) flight environment test (fig. 19). In this test, after a 1-hour exposure to full equivalent solar heating, the temperature within the capacitor module was 353 K, and the rise was about 11.6 C$^{o}$. The application of derating criteria (2) is thus: $353 + 2(11.6) = 376$. This hotspot temperature of 376 K is well within the allowable temperature rise criterion of 400 K.

Capacitors C1, C33, C35, and C37 were originally gelled-electrolyte tantalum capacitors employing elastomeric compression seals complying with MIL-C-3965. These seals are not adequate for space use, and new capacitors employing true hermetic glass-to-metal seals were selected. These were of a quality level comparable to those developed for Minuteman use, namely, 0.001 percent per 1000 hours at the 60-percent upper confidence level. They are manufactured under climate and dust-controlled conditions in manufacturing space set aside for high reliability part production, by especially selected and trained personnel. A special environmental laboratory was set up by the vendor for sampling tests. Very stringent specifications are applied to raw materials, and 100-percent culling tests and sampling tests are employed for unusually rigorous in-process control of the product.

Although an official military specification has not yet been attached to this part, the vendor has prepared his applicable specification in military format, and the quality level and degree of control are fully equivalent to a formal MIL specification part. A formal

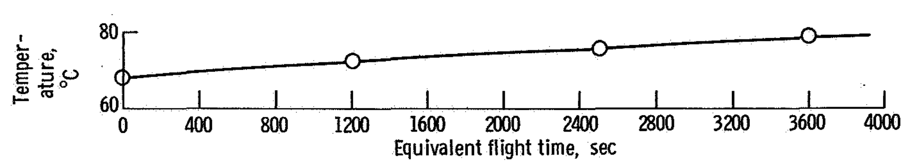


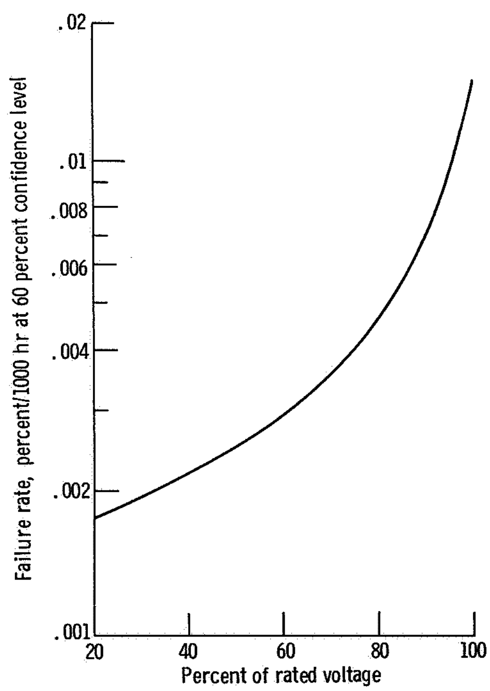

Figure 19. - Temperature rise in center of capacitor module in simulated flight environment. Maximum solar heating. (Thermal equilibrium achieved prior to T - 0 with forced-air cooling (25° C).)

source control drawing or specification was imposed on the vendor by the vehicle contractor for this and all other capacitors.

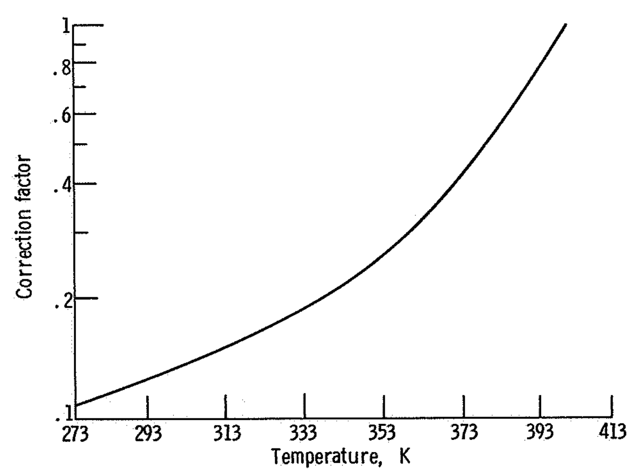
New capacitors C6, C7, C31, C34, C35, and C38 are all foil-tantalum types specified to MIL-C-38102. Rigid production and testing practices similar to those already described are also employed for these capacitors, and source control specifications apply. Approximately 14 million unit hours of life-test data at 398 K and 100 percent rated voltage have yielded a failure rate of 0.014 percent per 1000 hours at a confidence level of 60 percent. The curves of figure 20 are used to determine failure rates as functions of voltage and temperature (from vendor data). Since a 50-percent derating factor is used for capacitors in this inverter, and an average temperature of about 343 K for a 1-hour mission, the failure rate under these conditions is predicted to be $0.0026 \times 0.22 = 0.00057$ percent per 1000 hours at a 60 percent confidence level.

Finally, new metallized paper-film capacitors are also employed, to specification MIL-C-14157, for C3, C4, C5, C8, C9 to C14, and C32. Originally these capacitors failed intermittently because of lead detachment due to the small number of layers in the smaller sizes. The MIL-C-14157 capacitors are extended-foil types with improved mechanical and electrical stability.

The sole remaining capacitor is a glass type manufactured and tested to specification MIL-C-11272. No problems were encountered with this part.




(a) Applies for a temperature of 398 K only.




(b) Adjusts part (a) for other temperatures.

Figure 20. - Foil-tantalum capacitor derating curves (to military specification MIL-C-38102).

It is apparent from the foregoing discussion that special emphasis was placed on the use of MIL standard capacitors. Certainly one compelling reason for this choice is simply that they are made in large (and controlled) quantities.

## Semiconductors

A brief description of the operation of the silicon-controlled rectifier (SCR) is given to aid in understanding what follows. An SCR is a solid-state semiconductor NPNP (or PNPN) four-layer device. The PNPN structure may be considered to consist of a PNP and an NPN transistor with a common collection junction. The device has three electrodes: anode, cathode, and gate. An SCR will block the flow of current in either direction. When a suitable voltage (or current) is applied to the gate, current flows from the anode to the cathode, and through the load circuit. If the polarity of the applied voltage is reversed, the device will again prevent the flow of current, but now the gate electrode loses control. The SCR is thus equivalent to a rectifier except that the gate initiates conduction at the desired time. Also, when conduction starts, the gate loses control. Conduction then continues until the anode-cathode current drops below a value called the holding current. After turnoff, the gate control again becomes effective. The SCR is thus the solid-state analogy of a gaseous thyratron tube, or a latching relay.

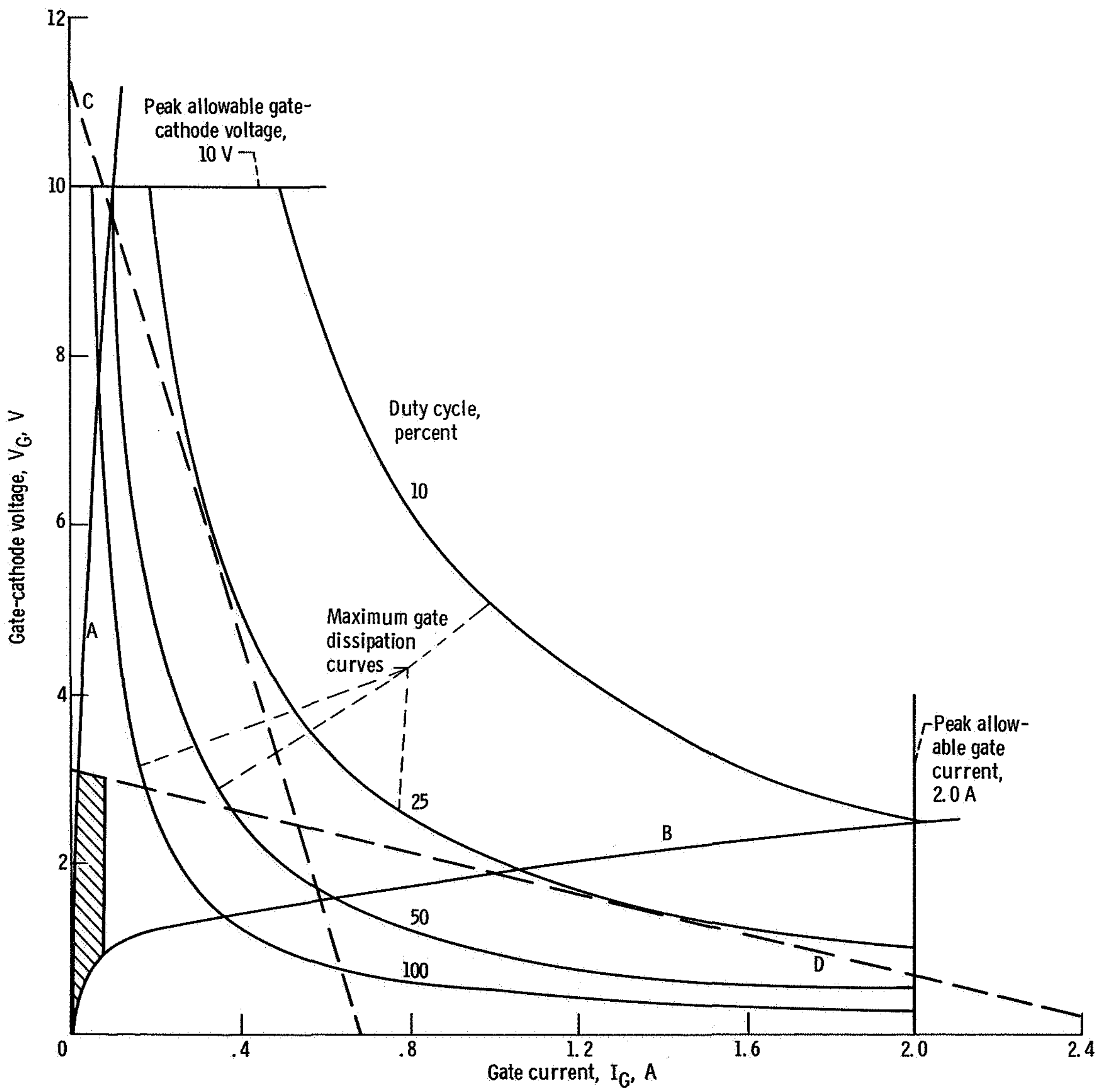
Chief among the limitations of the type 2N683 or C35 series SCR formerly employed was its 398 K maximum rated junction temperature and 200-volt repetitive peak inverse rating. A new part, type C38H, has a maximum junction temperature rating of 423 K, and a corresponding voltage rating of 250. In addition, full X-ray and preconditioning requirements were imposed. The contractor has imposed control specifications on the vendor such that the acceptable quality level (AQL) is 1 percent or better, which is superior to the requirements of MIL-S-19500/108/USN (ref. 19). (Added inspection and additional selection by the contractor have further improved the AQL by another order of magnitude.)

Changing from 398 K SCR's to 423 K gave the same improvements shown in the following table:

| Inverter | SCR case temperature, K | | |
|---|---|---|---|
| | 298 | 336 | 366 |
| | Combined failure rate, percent/1000 hr | | |
| Old (398 K SCR) | 0.332 | 1.003 | 1.867 |
| New (423 K SCR) | .317 | .813 | 1.416 |
| Percent improvement of 423 K SCR over 398 K SCR | 4.5 | 18.9 | 24.2 |

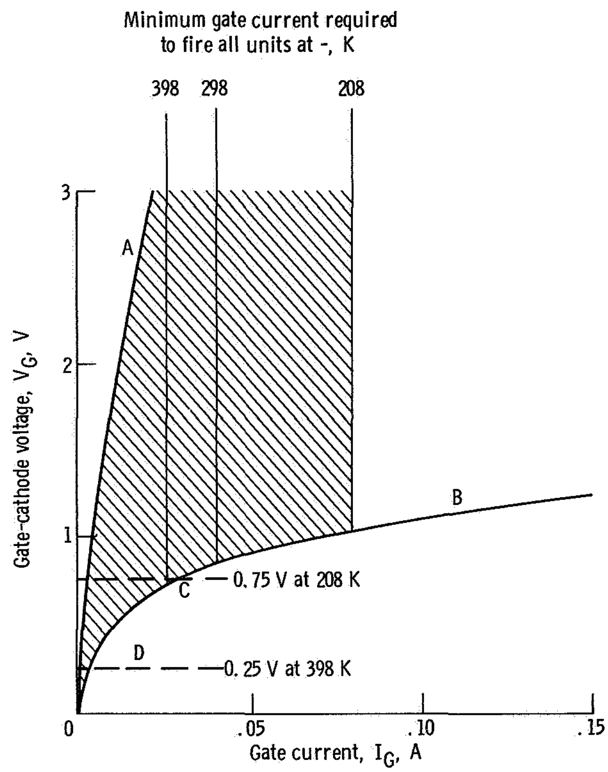
In addition to these parameters, the gate pulse firing characteristics are of special concern, especially at low temperatures. The relation between dc or steady-state characteristics and the pulse-firing characteristics are shown in the following series of figures. Figure 21 shows the steady-state control characteristics, and figure 22 shows the effect of pulse width on sure-fire capability of the SCR's (vendor data).

The SCR's are used in several places in the inverter, each with different degrees of criticality in firing. The applications are (1) regulators (CR27, CR28, CR31, CR32, CR36, CR38); (2) commutators (CR29, CR30, CR33, CR34, CR37, CR38); (3) shift register core driver (CR12); and (4) overload circuit (CR40). Criteria were set up for




(a) Curves A and B indicate limit values of the voltage-current characteristic between gate and cathode. Lines C and D indicate the maximum limits of load lines at 25 percent duty cycle.

Figure 21. - Gate and firing characteristics of 2N681 series SCR.




(b) Curves A and B indicate limit values of the voltage-current characteristic between gate and cathode. Lines C and D indicate the maximum gate-cathode voltage that will not fire any units. Shaded area represents locus of possible firing points between 208 and 398 K.

Figure 21. - Concluded.

these various applications when driven by pulses of 1 microsecond width at -20$^{\circ}$ C (253 K) as shown in figure 23.

Aside from SCR's, three transistor types S2N657A, 2N2219, and 2N491B are used, as well as a number of diodes. Former "MESA" construction was replaced with epitaxial planar design in compliance with Marshall Space Flight Center specifications which require 100-percent inspection and preconditioning (power "burn-in"). The relevant Marshall specifications are: MSFC-85M01109, MSFC-85M01309, MSFC-85M01310, MSFC-85M01673. Several military specifications were retained: MIL-S-19500/124A, MIL-S-38103/120, MIL-S-19500/251A. However, in these cases, added inspection and burn-in were imposed by vendor control specification.

| Curve | SCR series | Temperature, K | 100 percent gate voltage, V | Firing circuit short-circuit impedance, ohm |
|---|---|---|---|---|
| A | 2N1770A | 208 | 3 | 20 |
| B | 2N1770A | 298 | 3 | 20 |
| C | 2N681 | 298 | 5 | 25 |
| D | 2N681 | 208 | 5 | 25 |
| E | 2N1909 | 298 | 5 | 25 |
| F | C5 | 298 | 3 | 20 |

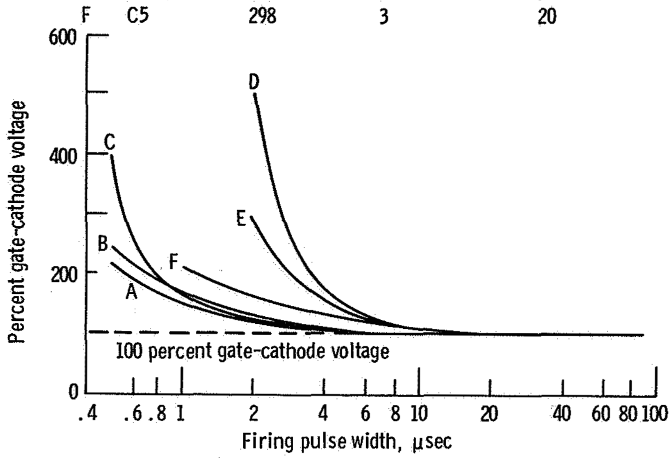



Figure 22. - Gate voltage required for short-firing pulse duration of SCR's.

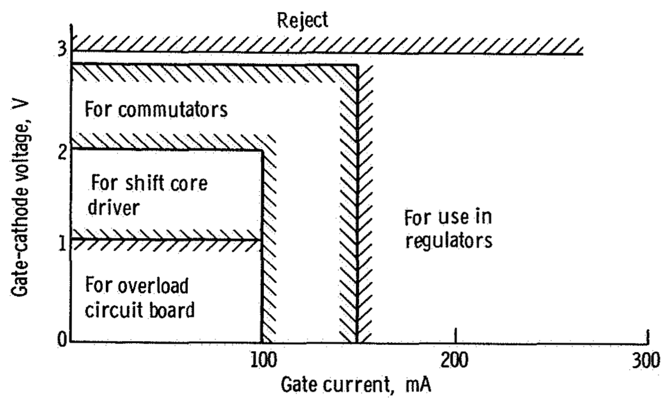



Figure 23. - SCR selection criteria (1 µsec pulses at -20° C (253 K).

## Resistors

Most of the resistors used in this inverter (or virtually all discrete component electronic equipment) are of the molded-composition type. Literally, billions of this kind of piece part have been manufactured and used by the radio and electronic industry for decades, and the quality and value levels have become quite advanced. MIL specifications R-11 and R-3900B apply, and these parts, made by the same vendor used for this inverter, have been approved for Minuteman use. Marshall Specification MSFC-PPD-600 also applies. Production and inspection are highly automated; continuity of production is quite important. There are a number of proprietary aspects to the manufacture, such as the exact composition of the resistive element and phenolic binder, and the pressures and temperatures used in its molding and curing. Nevertheless, there are some internal design features relating to reliability which are of interest. One is the use of integral "collars" on the axial leads to prevent mechanical separation from the resistive element and its insulating jacket. Another is the use of a suitable alloy for the leads which will form, solder, and weld well. Still another important consideration is the control and predictability of small incremental resistance changes due to humidity, temperature, and aging effects. The most important factors relating to these well-established parts are vendor experience and dependability and the use of conservative derating design practices. Figure 24 (vendor data) shows the effect of ambient temperature on voltage or wattage derating, as specified by the vendor. The vendor also specifies maximum resistance changes of 4 percent and -6 percent (with 99 percent confidence), for conditions of one-half rated load, 343 K ambient temperature, and 10 000 test hours for all values of resistance and wattage rating.

From Military Standardization Handbook on Reliability Stress and Failure Rate Data for Electronic Equipment - MIL-HDBK-217A (ref. 22), following are failure rates for MIL-R-11 type fixed composition resistors, in terms of temperature and power ratio. (Power ratio is defined as operating power divided by rated power).

The failure rate of 0.0035 per million hours remains constant over the range 288 K (at a power ratio of 1.0) to 343 K (at a power ratio of 0.1). The failure rate rises to 0.16 over the range 343 K (power ratio of 1.0) to 398 K and a power ratio of 0.1.

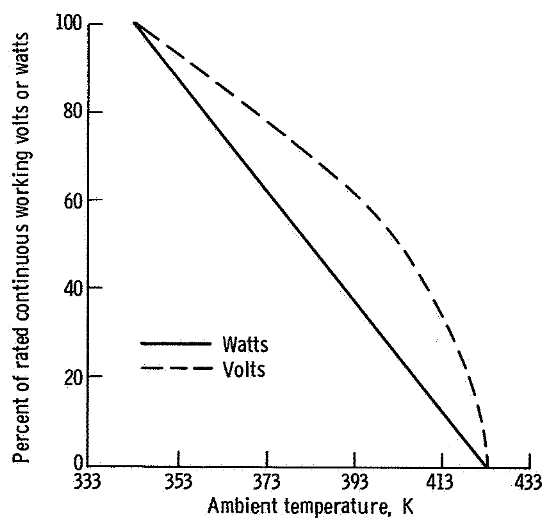



Figure 24. - Molded composition resistor derating curves. At ambient temperatures above 343 K, the change in resistance, after 1000 hours, will be within the limits of -6 percent to +4 percent provided the working voltage is derated in accordance with the dashed curve.

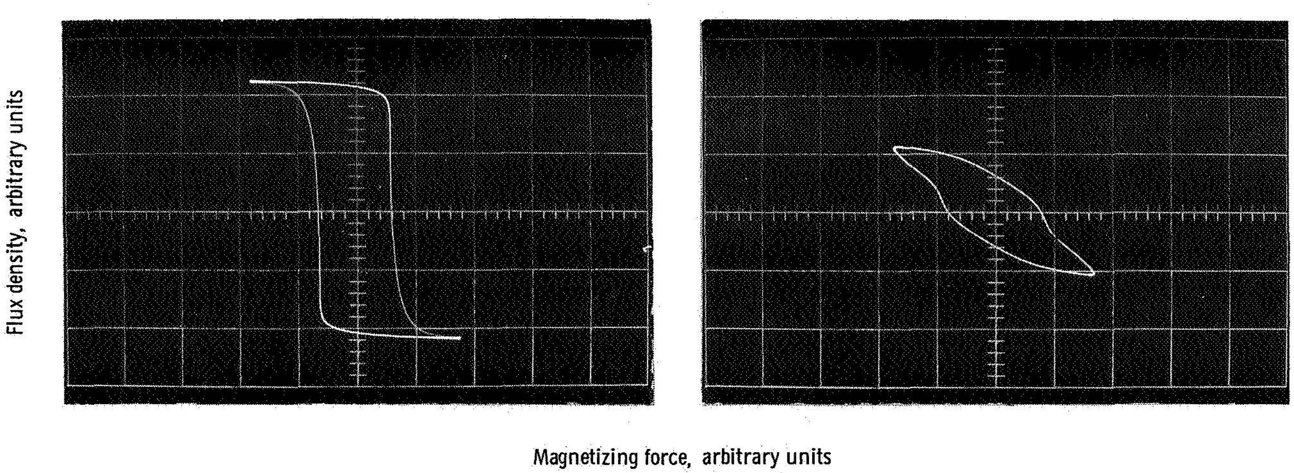
The Centaur inverter has a maximum ambient temperature of about 328 K at the end of long coast missions, and the power ratio is less than 0.6 in all cases. For this class of service, MIL-HDBK-217A (ref. 22) recommends a K factor of 50 for missile use. (The K factor is a multiplier based on field experience, where stresses of various natures are imposed, not specifically accounted for in MIL-HDBK-217A data.) From MIL-HDBK-217A (ref. 22, p. 7.5-11), the failure rate is given as 0.12 per million hours at 363 K. These failure rates do not include the effects of preconditioning, screening, vendor selection, special handling, or other quality assurance controls over and above normal controls. Since the resistors for this inverter do receive special attention, the field usage failure rates given are conservative.

Resistors R1, R12, and R87 have been changed to established reliability types used on the Minuteman program to comply with MIL-R-38101. Wirewound resistor R14 was formerly procured to specification MIL-R-10509. It has been replaced with an established reliability part to specification MIL-R-55182. All wirewound variable resistors are now being procured to vendor control specifications including 100 hours at full power and temperature, temperature cycling to MIL-STD-202 (Method 102, Condition D), and 20 turns rotation test. Lot acceptance criteria, traceability, and change control procedure were established according to MIL-D-70327.

Resistors R61 and R63 were overstressed. This condition was corrected by applying a uniform derating policy of at least 50 percent on all resistors.

## Magnetics

The nature of the "double-pulse" problem has previously been described. A clue to the solution lay in the extreme stress sensitivity of the special magnetic material used in winding the cores. A vacuum-impregnating process deposited epoxy on the 1-mil




(a) Good cores. (b) Defective cores.

Figure 25. - Variation of magnetizing force as function of flux density for shift-core registers.

magnetic tape, which, upon hardening, set up enough strain to affect the magnetization (B/H) curve adversely (see fig. 25). The solution was to spray the cores rather than vacuum-impregnate. The resultant output from a typical shift register then appears as in figure 7, which also serves as the basis for shift register selection.

Another problem involving epoxy concerned the use of conformal coating on printed circuit board assemblies. NASA Specification NPC 200-4 and MSFC-PROC-257A clearly call for the use of "tight vinyl or fiberglass sleeving on glass and other fragile parts before application of epoxy coating." This was not being done. Although the thermal coefficient of expansion for typical epoxy coatings was not available, experience has shown that at low temperatures (around 273 K), sufficient stress is set up to crack glass diodes and the like. Another coating, with less hazardous properties, was desired. After considerable research and testing, a polyurethane coating was chosen, with a thermal coefficient of expansion of -0.227 ppm at 218 K and -15 ppm at 335 K. Boards coated with this material successfully passed vibration, shock, and thermal-vacuum testing according to environmental specification 55-00200E (see appendix).

## CIRCUIT CHANGES

Zener diode CR1 was changed from a rating of 22 volts (1 W) to 18 volts (10 W). This was done to provide a minimum supply voltage of 18 volts to the oscillator at all times and to improve regulation by lowering dynamic impedance. Formerly, if the dc input voltage to the inverter momentarily fell below 22 volts, because of transients (such as those caused by pyrotechnic firing), the oscillator would cease functioning during this interval causing a brief inverter dropout.

Resistor R60 was changed from 470 to 91 ohms to ensure consistent starting of the internal Royer power sypply under all environmental conditions.

Transistors Q6 and Q7 were changed from 2N656 to S2N657A because the latter has a higher breakdown voltage rating from collector to emitter ($BV_{CE}$, 100 instead of 60). The 2N657A has a higher power rating (5 instead of 4 W), and the 2N657A is designed for pulse operation; the old transistor was not.

Other inverter reliability improvements consisted of deletion of unnecessary parts or replacements with fewer parts. For example, the original overload bypass circuit was deleted. It consisted of half of the input filter (which introduced unnecessary impedance): transformer T6, R85, CR84, CR85, and CR86.

## MANUFACTURING OPERATIONS

The modular concept of assembly has previously been described. An added benefit from the use of this technique is that subassembly testing of major components may be done in a complete operating inverter set up on a breadboard (fig. 26). The modules so tested are

(1) Output transformers
(2) Inductor assembly
(3) Capacitor assembly
(4) Current transformer assembly
(5) Filter assembly
(6) Circuit boards

The breadboard is unique because it offers the possibility of parts interchange to check out the effect of component parameter shifts on inverter operation. Also, it represents an economical solution to testing requirements by replacing more usual expensive and lavish test consoles. This is appropriate for the research and development approach employed. Modules are then installed as a set for a specific inverter.

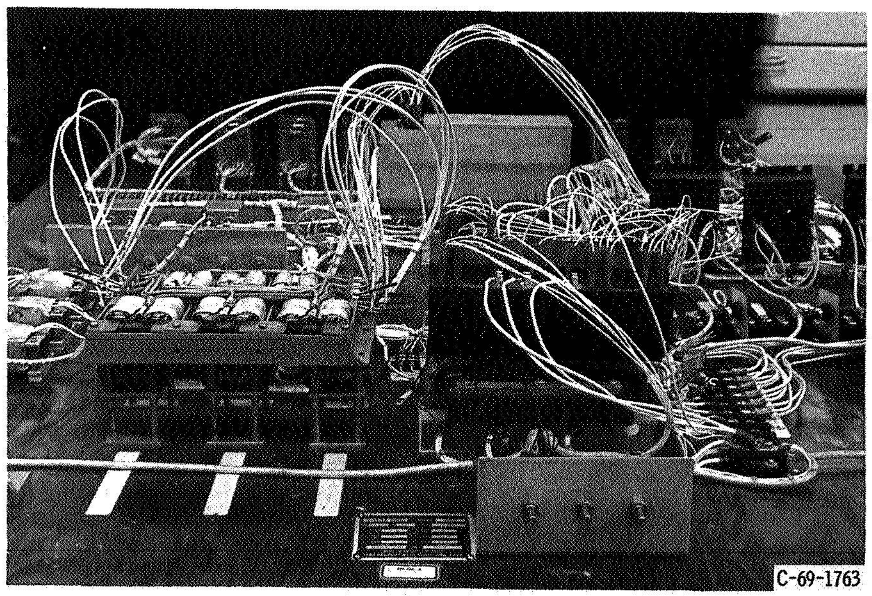



Figure 26. - Module static inverter used in acceptance test.

## CONCLUSIONS

An improvement program to upgrade the quality and reliability of the Centaur solid-state inverter was successfully completed. The following results and findings were obtained:

1. Significant increases in thermal design margins were obtained with a threefold approach by consisting of

a. Choosing parts, where available, with higher temperature operating limits

b. Improving thermal conductivity from hotspots to external radiating surfaces

c. Providing larger heat sink volumes, so as to increase heat flow from hotspots

2. Improved case structural design and modularizing major subassemblies reduced mechanical resonances and increased vibration resistance of the inverter.

3. The choice of established reliability parts wherever possible, rather than ordinary "MIL-SPEC" or commercial-grade parts contributed to overall improved reliability.

4. Coordinated efforts of government and contractor cognizant engineers in a concentrated drive obtained successful and timely results.

Achievement of the necessary level of reliability is primarily the responsibility of the design engineer. Once a design is established, subsequent efforts during production and use cannot produce any improvement in the inherent reliability, but can only correct poor workmanship or misapplication of parts. High reliability is not the result of a single design analysis. Rather, it is obtained through intense planning and a series of progressive actions consisting of quantitative and qualitative controls applied at every stage of the design process. Although the work described in this report was confined to a solid-state component with conventional size parts, the methodology and ground rules apply to a large class of electronic equipment employing similar parts.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 21, 1969,
497-91-00-39-22.

# APPENDIX - INVERTER SPECIFICATIONS, OPERATION, AND DIAGRAM AND RELIABILITY OF ASSOCIATED ELECTRONIC COMPONENTS

The Centaur inverter converts 28 volts direct current to three-phase, 115-volt, 400-hertz alternating current. It is rated at 650 volt-amperes and 1 to 0.8 lagging power factor. Performance specifications are presented in the next section, and the inverter circuit diagram is shown in figure 27. Parts designations used throughout this report are identified on the circuit diagram. This inverter consists of the following stages:

(1) A crystal oscillator for generating a stable signal of precise frequency
(2) Countdown circuits to obtain pulses of the correct frequency and amplitude
(3) A ring counter to store and sequentially release control pulses to trigger the SCR's for three-phase operation
(4) Three SCR power stages, including transformers and filters
(5) Magnetic amplifier-regulators for each phase
(6) A low-voltage direct-current power supply, for internal use
(7) An overload protection circuit

For further details on the design and operation of this inverter, see reference 7.

## SPECIFICATIONS FOR CENTAUR INVERTER

| | |
|---|---|
| Weight, lb; kg | 50; 22.7 |
| Size, in.; cm | 10 by 5 by 16; 25 by 13 by 41 |
| Input voltage, V dc | 25 to 30 |
| Output power: | |
| V-A | 650 |
| phases | 3 |
| Output voltage: | |
| V ac | 115 |
| Output connection | Wye |
| Output regulation: | |
| Voltage from no load to full load, V rms (±2.5 percent) | 115 |
| Output frequency, Hz | 400 |
| Phase accuracy and stability, deg | 120±2 |
| Efficiency at full load, percent | 67 |
| Ambient operating temperature range, K | 277 to 299 |
| Power factor | 0.97 lead to 0.97 lag |

Overload capability is 125 percent of rated full-load current for 60 seconds.

Short circuit protection: The output load may be varied from short circuit to open circuit without injury to the inverter.

Output regulation: Output voltage and frequency is regulated within 100 milliseconds of any change in output load.

Environmental: The inverter is capable of normal operation in a free space environment for at least 4 hours under either maximum or minimum solar radiation conditions.

The inverter is capable of normal operation in an atmospheric pressure range of 0.01 micrometer to 76.2 centimeters ($101.4\times10^3$ N/cm$^2$) of mercury and in relative humidities up to 100 percent. The case is not pressurized, but vented to the atmosphere. The vibration environment is specified in figure 28.

The circuit diagram of the inverter is shown in figure 27.

## ANNOTATIVE NOTES ON RELIABILITY OF ELECTRONIC PARTS AS RELATED TO THE INVERTER

This section of the appendix provides a brief introduction to the current state of the art. As technology advances, aerospace components, as well as industrial and military equipment and consumer products, become more complex. They contain more piece parts, the parts are more intricate, and specifications relating to them become more critical and definitive. The military services and the NASA impose quantitative reliability requirements on their prime aerospace contractors. These large companies are not self-sufficient; that is, they do not make everything they sell. Supplier products constitute a significant portion of large systems, and vendors participate in meeting the overall system requirement. The Defense Department has set up an elaborate system of military specifications, upon which the NASA relies heavily. Military (MIL) specifications are used because historically they have served to standardize and upgrade the quality of electronic parts, and because requirements and funding have been sufficient to develop and continue production of high-grade parts. In addition to MIL specifications, the NASA has certain specifications of its own, which in some cases (because of space environments) are even more demanding than those of the military. As pointed out in reference 19, heretofore, failure rates of 0.1 to 0.01 percent per 1000 hours have been considered adequate. Today, however, the critical demands of space flight require failure rates of 0.001 percent per 1000 hours or better. Naturally, the more reliable a device, the longer it takes to demonstrate or measure its reliability.

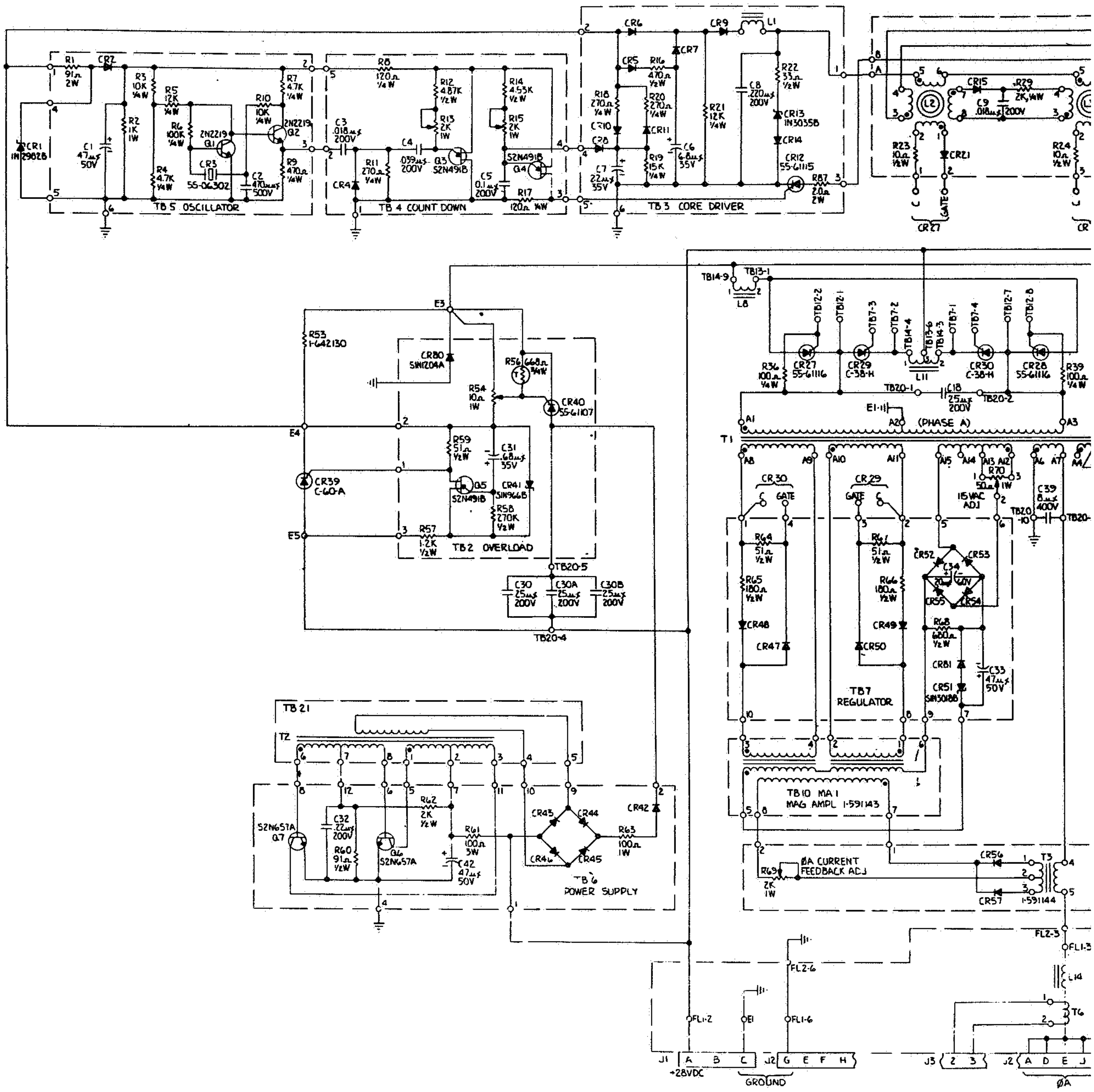
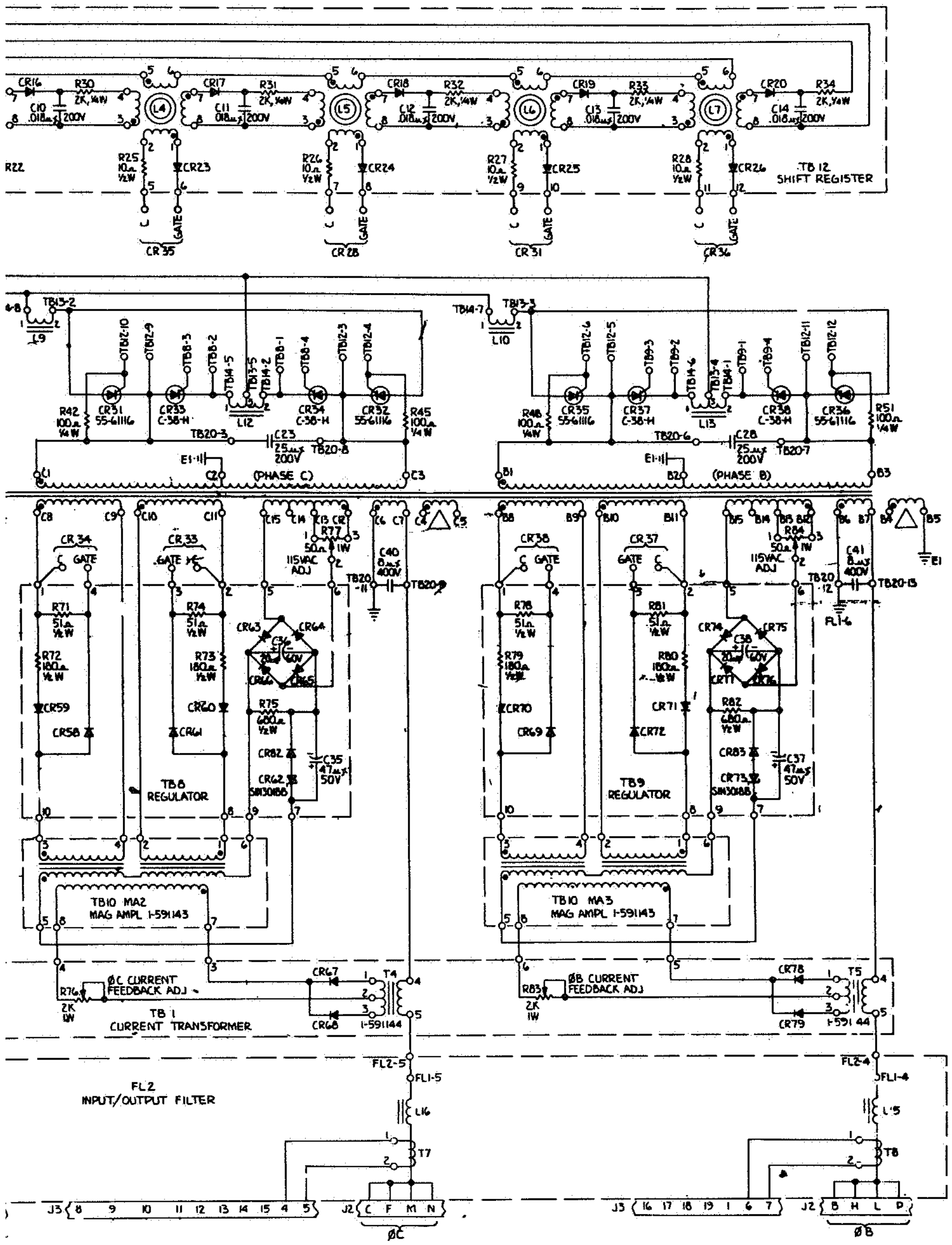
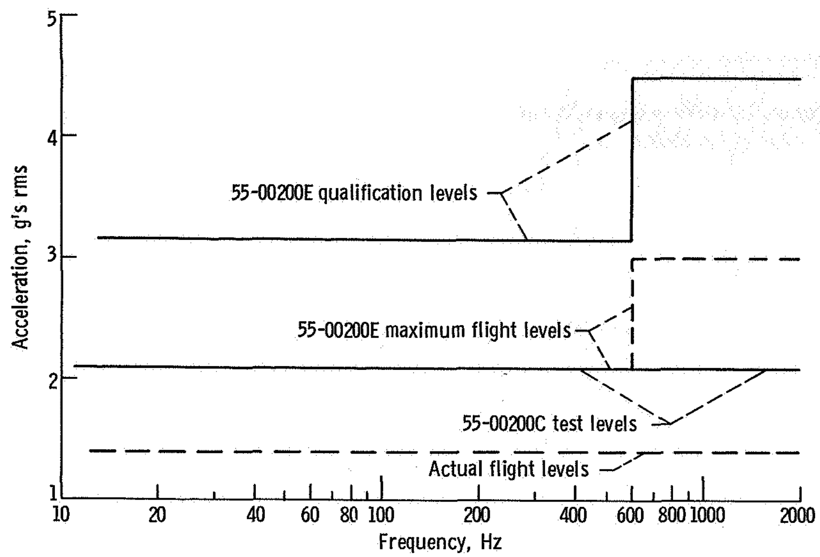


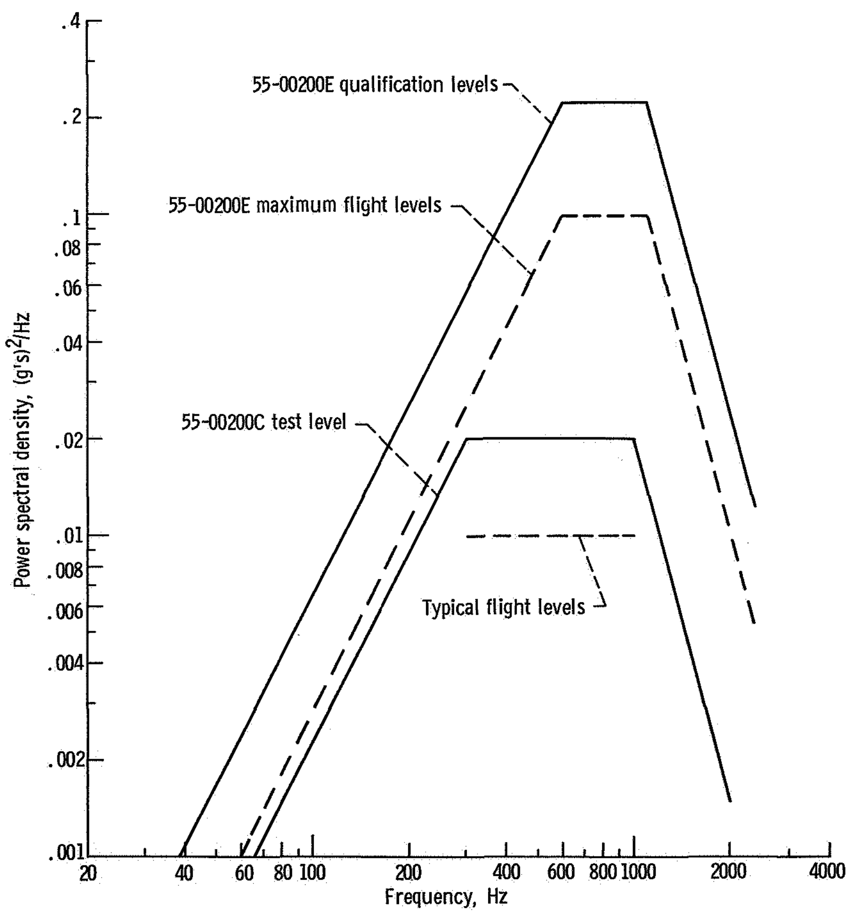
Figure 27. - Circuit diagram



of Centaur inverter.




(a) Sine wave excitation.




(b) Random excitation.

Figure 28. - Vibration test levels for forward equipment shelf.

The Defense Department has also recognized the need for a superior class of specification calling for even greater reliability than usual, for example, with regard to nuclear submarines and the Minuteman missile. The system requirements for the Minuteman have lead to the initiation of a large-scale reliability improvement program which has achieved outstanding results. A proven high standard of reliability has been attained that represents a goal for other space projects (ref. 22). Capacitors, for example, have attained field failure rates of 0.006 per million hours for paper types and 0.007 per million hours for tantalum. Composition resistors experience yields a rate of 0.0018 per million hours and silicon semiconductors range from 0.002 to 0.038 per million hours. Diodes tend to average at the low end of this range. These failure rates apply for an electrical stress of 20 percent of rated capacity and a temperature of 313 K.

In addition to the Minuteman specification, NASA also employs semiconductor specifications developed by the Marshall Space Flight Center. These are designated by the prefix "S" before the commercial part number.

Some of the MIL (and NASA) specifications relating to this inverter are:

Semiconductors:

MIL-S-19500/124A
S-38103/120

MSFC-85 MO/309
85 MO/310
85 MO/673
85 MO/102
85 MO/109

Capacitors:

MIL-C-3965C
C-11272B
C-14157C
C-38102

Resistors:

MIL-R-11A
R-38101/2A
R-55182

The testing and sampling procedures called out in parts specifications are based upon MIL Standard 202 and MIL Standard 105A. The first specification describes test methods for piece parts, and the second describes sampling plans to determine the acceptability of products procured for government contracts.

Normal sampling plans, such as those outlined in military specifications or Radio, Electronics, and Television Manufacturer's Association (RETMA) Sampling Procedure Bulletin No. 42, identify Acceptable Quality Levels (AQL's) from 0.1 to about 8 percent (ref. 2). (AQL is a nominal value expressed in terms of percent defective; that is, it is the number of defective units in any lot divided by the total number in the lot, multiplied by 100.)

The RETMA Bulletin raises the question: "How good should parts be?" The answer depends on the number of series-type parts in the equipment and the desired acceptance level, or reliability, of the finished equipment. For example, if the equipment is simple, has approximately 100 parts or so, it is easy to produce acceptable equipment from parts whose initial acceptance quality level is of the order of 0.1 percent.

When equipment becomes more complex, however, (or more demanding) and contains several thousand parts, the order of magnitude of initial acceptance quality level required is better than 0.01 percent. Laws of mathematical probability state that the reliability of a complete unit will not be governed by the average quality of the parts, but rather, will be lower even than that of the weakest component. In simple words, these laws state that the reliability of the complete system depends exponentially on the number of individual parts.

Unfortunately, parts specifications lag behind the state of the art because of the time involved in gaining acceptance by the services and by industry (which are fundamentally conservative).

For some advanced pieces of equipment it may be necessary for the designer to select and specify a nonstandard part (one on which there is no military specification). The designer who does so bears the burden of proof to show by specification, performance, or environmental tests that a standard component will not do the job. Naturally, he must also show by test that the proposed nonstandard part will perform satisfactorily in the environmental restrictions of the equipment. Further discussion of nonstandard parts is given in reference 2.

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